Simulation and Experimental Research on Transverse Random Vibration of Typical Valve for Launch Vehicle

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Abstract. In order to effectively suppress the transverse random vibration of a class of irregular shape and structure valve for launch vehicle in the ground test, adopting the method of combining finite element simulation and experiment, the influence of different structure tools on the transverse vibration of the valve is investigated. Moreover, the impact of arrangement position of valve and semi-circular tool assembly on transverse vibration of valve is studied. Based on the analysis of the influence of tooling of different structures on the transverse random vibration of the valve, it is proposed that semi-circular fixture can effectively reduce the transverse vibration for this kind of valve. Furthermore, when placed in the center of vibration table or near the vibration source, can decrease transverse vibration of the valve remarkably.

1. Introduction

The valve is an important element of the pressurization and delivery system for liquid launch vehicle. It is used to realize the functions of gas delivery, cut-off, regulation, discharge, overpressure protection, and propellant addition and discharge, overflow and so on [1], therefore, sufficient ground vibration tests must be carried out to ensure the reliability of its quality for liquid launch vehicle valve during the process of design and development. The tested valve is installed on the vibration table through the test tool, and the combination of test tooling and vibration table is used to simulate the mechanical platform environment generated during the expected use of the valve in the ground vibration test. In addition, some valves have complex structures, the valve may be damaged seriously in the process of test because of the existence of transverse vibration. We define a vibration table is a datum plane, the direction of motion is axial motion, the direction perpendicular to the axial movement is the transverse movement direction. The transverse vibration [2] is usually expressed by the acceleration in the transverse direction divided by the acceleration in the axial direction. The transverse vibration can be limited to the minimum by means of shaking table control technology, tooling design and changing the fastening mode in engineering practice. The typical valve design requires that the transverse vibration of random vibration should not exceed 50% of the main vibration.
Experts and scholars at home and abroad have conducted extensive and in-depth research on lateral vibration in recent years. The research results of Lei et al. [3] show that when trains meet in the tunnel, the lateral vibration of trains intensifies, safety and stability of trains are reduced significantly. Li et al.[4] studied the failure of bolted structures under lateral vibration, the results indicated that the ordinary bolt connection will fail due to the nut loosening, while for the anti-loose nut, the pre-tightening force will be partially reduced due to the nut loosening, and then the bolt root fatigue fracture will lead to complete failure under the transverse harmonic vibration. Li et al. [5] established a first-order sensitivity model of the natural frequency of the barrel to the change of the support position in order to solve the problem of the impact of the barrel vibration on the shooting accuracy. The model was used to optimize the search for the support position, and finally from the frequency and vibration shape aspects determined the optimal support position with the smallest lateral vibration response of the muzzle. A. Jafarzadeh Jazi [6] reported concentrated mass installed on the nano beam has an important influence on the transverse vibration. Daniel Cintra [7] studied the influence of uniaxial intermittent and permanent harmonic excitation on the lateral vibration of beams. The results show that lateral vibration is the basic form of beam vibration, the lateral vibration will occur, when the excitation frequency is much greater than the lateral vibration frequency. K.Torabi [8] used the variational iteration method to study the linear and nonlinear lateral vibration of Euler-Bernoulli beams with multiple concentrated masses, and considered the influence of concentrated masses on natural frequencies and modal shapes.

2. Finite element analysis and experimental study

2.1. Finite element analysis

ANSYS finite element software is used to carry out finite element simulation calculation of random vibration of the typical valve of the launch vehicle in this paper. The conditions of random vibration are shown in Table 1. The structure of vibration tooling includes four structural forms: square tooling, semi-square tooling, circular tooling and semi-circular tooling. The valve and the tooling, the tooling and the vibration table are all connected by a fixed connection. The combination of the valve and the tooling is placed in the center of the vibrating table, and the random vibration is simulated by the method of spectrum analysis. The X direction is defined as the radial direction of the valve body, the Y direction is the direction perpendicular to the vibration table, and the Z direction is the axial direction of the valve body. The finite element model is shown in Figure 1.

| Frequency range(Hz) | Vibration level power spectral density (g²/Hz) | Duration of test T=3.0min |
|---------------------|---------------------------------------------|--------------------------|
| 20~100              | 3dB/oct                                     | 19.88                    |
| 100~250             | 0.28                                         |                          |
| 250~350             | 0.80                                         |                          |
| 350~1000            | 0.40                                         |                          |

![a) Square tooling] ![b) Semi-square tooling] ![c) Circular tooling] ![d) Semi-circular tooling]

**Figure 1.** Finite element model
The transverse vibration of four points on the base of the valve is assessed. The four points are distributed along the circumferential direction, and the angle between the four points is 90°. The position distribution is shown in Figure 2.

![Figure 2. The diagram of test points distribution on valve base](image)

2.2. Experimental study
The vibration table was tested before the random vibration test. The table size of the vibration table is 600mm×600mm×40mm, and the sensor distribution diagram is shown in Figure 3. CH1 and CH3 are control sensor channels, CH5, CH6, and CH7 are the three directions corresponding to the response sensor, and CH5 channel tests the main vibration direction. The test conditions are input according to the vibration conditions shown in Table 1. The test result data is shown in Table 2. From the test data in Table 2, it can be concluded that the vibration table for the test meets the transverse vibration amount specified in GB/T 13310-2007 and meets the test requirements. The diagram of vibration test is shown in Figure 4, the combination of valve and semi-circular tooling is placed in the center of the shaking table for random vibration test.

![Figure 3. The diagram of vibration table sensors distribution](image)

| CH1   | CH3   | CH5   | CH6   | CH7   |
|-------|-------|-------|-------|-------|
| Random excitation | 19.85 | 19.23 | 19.57 | 0.5427 | 0.7029 |

![Figure 4. Diagram of vibration test](image)

3. Result and analysis
The combination of tooling and valve with different structures is placed in the center of the platform for simulation and testing. The assessment index is the root mean square acceleration. The result data is...
shown in Table 3 to Table 6. The bolded data is the transverse vibration exceeding the standard 50% of its main vibration volume. The data in brackets in Table 6 are experimental data.

| Test Point | Radial direction (vibration direction is X) | Axial direction (vibration direction is Z) |
|------------|------------------------------------------|------------------------------------------|
|            | X | Y | Z | Z | Y | X |             | X | Y | Z | Z | Y | X |
| 1          | 18.76 | 4.28 | 6.96 | 14.28 | 4.03 | 11.21 |             |   |   |   |   |   |   |
| 2          | 11.63 | **6.86** | **7.62** | 6.99 | **6.87** | 4.99 |             |   |   |   |   |   |   |
| 3          | 11.25 | 3.82 | **5.75** | 12.91 | 3.79 | **10.52** |             |   |   |   |   |   |   |
| 4          | 10.59 | **5.4** | **10.2** | 6.66 | **5.72** | **25.53** |             |   |   |   |   |   |   |

| Test Point | Radial direction (vibration direction is X) | Axial direction (vibration direction is Z) |
|------------|------------------------------------------|------------------------------------------|
|            | X | Y | Z | Z | Y | X |             | X | Y | Z | Z | Y | X |
| 1          | 19.66 | 4.3 | 6.91 | 14.71 | 4.05 | **11.28** |             |   |   |   |   |   |   |
| 2          | 13.86 | **7.46** | **8.05** | 9.05 | **7.57** | 5.1 |             |   |   |   |   |   |   |
| 3          | 11.21 | 3.84 | **5.77** | 12.78 | 3.81 | **10.74** |             |   |   |   |   |   |   |
| 4          | 11.94 | 5.59 | **20.72** | 7.45 | **5.89** | **25.97** |             |   |   |   |   |   |   |

| Test Point | Radial direction (vibration direction is X) | Axial direction (vibration direction is Z) |
|------------|------------------------------------------|------------------------------------------|
|            | X | Y | Z | Z | Y | X |             | X | Y | Z | Z | Y | X |
| 1          | 22.74 | 4.27 | 6.95 | 21.47 | 4.02 | **11.32** |             |   |   |   |   |   |   |
| 2          | 23.91 | 6.79 | 7.47 | 21.46 | 6.82 | 4.79 |             |   |   |   |   |   |   |
| 3          | 22.45 | 3.81 | 5.75 | 22.92 | 3.78 | **10.63** |             |   |   |   |   |   |   |
| 4          | 21.35 | 5.39 | **10.22** | 19.89 | 5.71 | 12.85 |             |   |   |   |   |   |   |

| Test Point | Radial direction (vibration direction is X) | Axial direction (vibration direction is Z) |
|------------|------------------------------------------|------------------------------------------|
|            | X | Y | Z | Z | Y | X |             | X | Y | Z | Z | Y | X |
| 1          | 19.87 | 4.31 | 3.49 | 22.89 | 9.87 | 5.76 |             |   |   |   |   |   |   |
| 2          | (19.69) | (6.25) | (2.79) | (20.93) | (8.63) | (4.32) |             |   |   |   |   |   |   |
| 3          | (20.29) | **16.33** | (4.09) | (20.23) | (4.77) | (1.84) |             |   |   |   |   |   |   |
| 4          | (20.89) | 7.76 | 5.82 | (25.73) | 9.62 | 5.49 |             |   |   |   |   |   |   |
| 2          | (20.42) | **14.4** | 3.79 | 23.25 | 7.32 | **4.64** |             |   |   |   |   |   |   |
| 4          | (19.72) | (12.9) | (3.63) | (22.66) | (5.03) | (2.27) |             |   |   |   |   |   |   |

As shown in Table 3, for square tooling, when the vibration direction is X, the transverse vibration of test point 2 along Y and Z direction exceeds the standard value, the transverse vibration of test point 3 along Z direction exceeds the standard value, and the transverse vibration of test point 4 along Y and X direction exceeds the standard value. When the vibration direction is Z, the transverse vibration of test point 1 along X direction exceeds the standard value, the transverse vibration of test point 2 along Y and X direction exceeds the standard value, the transverse vibration of test point 3 along X direction exceeds the standard value, and the transverse vibration of test point 4 along Y and X direction exceeds the standard value. A total of 11 values exceed the standard value. As shown in Table 4, for semi-square tooling, when the vibration direction is X, the transverse vibration of test point 2 along Y and Z direction...
exceeds the standard value, the transverse vibration of test point 3 along Z direction exceeds the standard value, and the transverse vibration of test point 4 along Z direction exceeds the standard value. When the vibration direction is Z, the transverse vibration of test point 1 along X direction exceeds the standard value, the transverse vibration of test point 2 along Y direction exceeds the standard value, and the transverse vibration of test point 4 along Y direction exceeds the standard value. A total of 10 values exceed the standard value. As shown in Table 5, For round tooling, when the vibration direction is X, the transverse vibration of test point 4 along Z direction exceeds the standard value. When the vibration direction is Z, the transverse vibration of test point 1 and 3 along X direction exceeds the standard value. A total of 3 values exceed the standard value. As shown in Table 6, for semi-circular tooling, when the vibration direction is X, the transverse vibration of test point 2 and 4 along Y direction exceeds the standard value. When the vibration direction is Z, there is no test point where the transverse vibration exceeds the standard value. A total of 2 values exceed the standard value.

In conclusion, the order of the influence of different structural forms of tooling on the transverse vibration is as follows: square tooling > semi-square tooling > round tooling > semi-circular tooling.

4. The effect of the layout position of the tooling on the vibration table on the transverse vibration

According to the results of simulation and experiment, the random vibration simulation and experiment research are carried out on the different layout position of the semi-circular tooling and valve combination on the vibration table. The five positions of the combination on the vibration table are shown in Figure 5.

![Figure 5. The Combination of Semi-circular Tool and Valve Placed in Five Positions on Vibration Table](image)

The result data of random vibration simulation and test at I position are shown in Table 6, and the result data of random vibration simulation and test at II-V position are shown in Table 7-10.

| Test Point | Radial direction (vibration direction is X) | Axial direction (vibration direction is Z) |
|------------|--------------------------------------------|-------------------------------------------|
|            | X       | Y       | Z       | Z       | Y       | X       |
| 1          | 24.88   | 13.13   | 6.97    | 22.71   | 14.69   | 7.09    |
|            | (17.68) | (10.31) | (2.99)  | (20.5)  | (12.37) | (5.31)  |
| 2          | 18.41   | 14.72   | 4.16    | 21.14   | 8.73    | 4.49    |
|            | (18.08) | (13.16) | (3.77)  | (19.3)  | (7.28)  | (4.51)  |
| 3          | 19.81   | 11.62   | 5.85    | 22.49   | 7.58    | 4.29    |
|            | (19.07) | (10.39) | (3.14)  | (21.02) | (5.62)  | (4.21)  |
| 4          | 16.18   | 16.62   | 4.21    | 25.36   | 4.78    | 4.27    |
|            | (17.68) | (16.56) | (4.32)  | (23.01) | (4.816) | (4.19)  |
As shown in Table 7, when the vibration direction is X, the transverse vibration of test point 1, 2, 3, 4 along Y direction exceeds the standard value; When the vibration direction is Z, the transverse vibration of test point 1 along Y direction exceeds the standard value. A total of 5 values exceed the standard value for II position. As shown in Table 8, when the vibration direction is X, the transverse vibration of test point 1, 2, 3, 4 along Y direction exceeds the standard value; When the vibration direction is Z, the transverse vibration of test point 1 along Y direction exceeds the standard value. A total of 5 values exceed the standard value for III position, the position and number of the transverse vibration exceeds the standard value same as II position. As shown in Table 9, when the vibration direction is X, the transverse vibration of test point 2, 4 along Y direction exceeds the standard value; When the vibration direction is Z, there is no test point where the transverse vibration exceeds the standard value. A total of 2 values exceed the standard value for IV position. As shown in Table 10, when the vibration direction is X, the transverse vibration of test point 2, 4 along Y direction exceeds the standard value; When the vibration direction is Z, there is no test point where the transverse vibration exceeds the standard value. A total of 2 values exceed the standard value for V position, the position
and number of the transverse vibration exceeds the standard value same as IV position. The above simulation results are in agreement with the test.

In a word, the combination of semi-circular tooling and valve at different positions affects the amount of transverse vibration in descending order: II=III>I=IV=V.

5. Conclusion

Through the above simulation and experimental analysis, the following conclusions can be drawn.

1) The vibration table used in the test is a factor that affects the transverse vibration. Before the vibration test, the vibration table should be adjusted to minimize the amount of transverse vibration that generated by the vibration table.

2) For the typical valve of launch vehicle, the semi-circular tooling is the best structure choice, which can reduce the transverse vibration effectively.

3) The combination of the valve and the semi-circular tooling is placed in the center of the vibration table or near the excitation source, which can effectively reduce the transverse vibration.

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