Affect of Elastic Displacement Limiter on Shock Response of Double-stage Vibration Isolation System

Yufeng Gong, Weicai Peng and Zhizhong Liu
National Key Laboratory on Ship Vibration & Noise, China Ship Development and Design Centre, Wuhan, Hubei 430074, China.
Email: Gong_yu_feng@163.com

Abstract. With a certain shock load, the displacement of the equipment with double-stage vibration isolation mounting may exceed the deformation limits of isolators themselves. Therefore, elastic displacement limiters usually need to be used in order to limit the relatively large displacement. In this paper, the response of the double-stage vibration isolation system was studied by numerical method. Effects of stiffness and assembled clearance of elastic displacement limiter on shock response were discussed.

1. Introduction
Naval vessels are inevitably attacked by underwater exploding weapons. The resulting shock load may cause a large number of equipment failures. At present, in order to ensure that the equipment can operate normally with underwater explosions, double-stage vibration isolation device are widely used to reduce the peak value of the shock acceleration received by the equipment itself and significant reduce the vibration response of equipment transmitted to the hull structure. Since the natural frequency of double-stage vibration isolation system such as floating raft is relatively low, the acceleration of equipment usually does not exceed the allowable value under the shock load. However, the displacement of the equipment may exceed the allowable value under the shock load, which leads to cable and pipe damaged by excessive deformation. Therefore, elastic displacement limiter were generally used to limit the displacement of the equipment. Once the parameter of elastic displacement limiter is selected unreasonably, it will cause the equipment suffer a severe secondary shock. Thus, it is of great significant to analyze the affect of elastic displacement limiter on shock response of double-stage vibration isolation system.

Researchers have carried out many researches on the influence of elastic displacement limiter on shock response of vibration isolation system [1]. Lin et al [2] discussed the shock response of a raft isolation system with limiters by multi-body dynamics method. Jiang et al [3] established an analytical model of nonlinear shock response of equipment using shock isolator with displacement limiter. The shock response of equipment was discussed by the pseudo-force approach. Han et al [4] studied the time-domain response characteristics of the single degree of freedom vibration isolation system with and without limiters by the finite element method. Ma et al [5] and Zhao et al [6] studied the influence of elastic displacement limiter with different stiffness and damping parameters on the shock response of the double-stage vibration isolation system respectively.

In this paper, a floating raft which is the typical double-stage vibration isolation system is taken as the research object. The effects of stiffness and assembled clearance of elastic displacement limiter on the shock response were discussed by finite element method, which includes the supported equipment's maximum acceleration and maximum displacement under certain shock load.
2. Mechanical Model Of Double-Stage Vibration Isolation System

Mechanical model of double-stage vibration isolation system with elastic limiter is shown in figure 1.

The dynamic differential equations of double-stage vibration isolation system with elastic limiter can be expressed in a local coordinate relative to the foundation. In the local coordinate, the generalized coordinate vector of each device can be expressed as:

\[
\{x\} = \{x_1, y_1, z_1\}
\]

The dynamic differential equations of device \(m\) in its own local coordinate can be expressed as:

\[
[m]\ddot{x} + [c] \dot{x} + [k]x = \{f\}
\]

Where \([TR]_m\) and \([TR]_n\) are the transformations matrix of rigid body \(m\) and rigid body \(n\) from local coordinate to global coordinate. \([TR]_k\) is the transformations matrix of isolator \(k\) from local coordinate to global coordinate.

The stiffness matrix of isolator \(k\) from in global coordinate can be expressed as:

\[
[k]_{mn} = \sum_{k=1}^{N} [TR]_m^{-1} [K]_k [TR]_n^T
\]

Where \([TR]_m\) and \([TR]_n\) are the transformations matrix of rigid body \(m\) and rigid body \(n\) from local coordinate to global coordinate. \([TR]_k\) is the transformations matrix of isolator \(k\) from local coordinate to global coordinate.

The stiffness matrix of isolator \(k\) from in global coordinate can be expressed as:

\[
[K]_k = [TR]_k [K] [TR]_k^T
\]

Due to the matrix \([TR]\) does not change with the state of elastic displacement limiter, only the change of \(k_{ij}\) needs to be considered. When the elastic displacement limiter works, the stiffness matrix becomes:

\[
[k]_{mn} = [k]_{mn0} + \Delta[k]_{mn}
\]

where \([k]_{mn0}\) is the stiffness matrix of isolator in local coordinate when elastic displacement limiter is not working. \(\Delta[k]_{mn}\) is the local stiffness matrix of elastic displacement limiter.

Since there is a nonlinear term in Equation (2), the corresponding numerical method is needed for shock response calculation. In this paper, the numerical calculation is carried out by the commercial finite element software ABAQUS.

3. Analysis of Influence of Limiter Parameters on Shock Response of Vibration Isolation System

3.1. Numerical Model

The floating raft vibration isolation system is composed of generators, upper isolators, upper elastic displacement limiters, lower isolators, lower elastic displacement limiters and floating raft. There are 2 generators installed on the floating raft by 8 upper isolators respectively. The floating raft is installed on the hull foundation by 8 lower isolators. The number of upper elastic displacement limiter is same as the upper isolators. The number of lower elastic displacement limiter is same as the lower isolators.
The numerical model is established by the commercial finite element software ABAQUS. The properties and dimensions of numerical model is listed in Table 1. The generators is simulated by hexahedral element while keeping the centre of gravity coordinates unchanged. Meanwhile, the floating raft is simulated by shell element. The mechanical properties of isolator and elastic displacement limiter is simulated by the connector element. The numerical model is shown in Figure 2. Shock load is an acceleration-time curve, which is shown in Figure 3. The positive amplitude is 341m/s². The negative amplitude is 172m/s². The positive pulse width is 8.7ms. The negative pulse width is 17.5ms.

### Table 1. The properties and dimensions of numerical model.

| Parameters                        | Values          |
|-----------------------------------|-----------------|
| Mass of generator $m_1$ (kg)      | 3000            |
| Height of generator $H_1$ (m)     | 1.00            |
| Length of generator $L_1$ (m)     | 2.64            |
| Width of generator $W_1$ (m)      | 1.30            |
| Height of raft $H_2$ (m)          | 0.45            |
| Length of raft $L_2$ (m)          | 5.60            |
| Width of raft $W_2$ (m)           | 4.48            |
| Mass of raft $m_2$ (m)            | 10000           |
| Stiffness of upper vibration isolator $k_1$ (N/m) | $1.5 \times 10^6$ |
| Stiffness of lower vibration isolator $k_2$ (N/m) | $1.9 \times 10^6$ |

3.2. Analysis of the Influence of Using Upper Elastic Displacement Limiter on System Shock Response

In order to analysis the influence of using upper elastic displacement limiter on system shock response, five examples with different stiffness of upper elastic displacement limiter were set up. There are not lower elastic displacement limiter in these examples, and the clearance of upper elastic displacement limiter is 5 mm. The stiffness of the upper elastic displacement limiter were set up. There are not lower elastic displacement limiter in these examples, and the clearance of upper elastic displacement limiter is 5 mm. The stiffness of the upper elastic displacement limiter is listed in Table 2. The shock response of examples A1-A5 were shown in Figure 4 to Figure 6.

### Table 2. Example of using upper elastic displacement limiter alone.

| Example ID | Stiffness of the upper elastic displacement limiter, $k_d$(N/m) | Clearance of the upper elastic displacement limiter, $D_d$(mm) |
|------------|---------------------------------------------------------------|----------------------------------------------------------|
| A1         | $1.0 \times 10^7$                                           | 5                                                        |
| A2         | $1.4 \times 10^7$                                           | 5                                                        |
| A3         | $1.8 \times 10^7$                                           | 5                                                        |
| A4         | $1.0 \times 10^7$                                           | 10                                                       |
| A5         | $1.0 \times 10^7$                                           | 15                                                       |
Numerical calculated results shows that the maximum acceleration of generator increases significant with the increasing of stiffness of the upper elastic displacement limiter. It indicates that the excessive stiffness of the upper elastic displacement limiter is harmful to the shock protection of generator. With the increasing of stiffness of the upper elastic displacement limiter, the maximum displacement of upper vibration isolator is decreasing slightly. This is because that the resistance force received by the upper vibration isolator increases with the increasing of the stiffness of upper elastic displacement limiter. This causes the displacement of the upper vibration isolator to be suppressed. The stiffness of the upper elastic displacement limiter has no obvious effect on the maximum displacement of lower vibration isolator. This is because the displacement of the lower vibration isolator is related to the inherent characteristic of the double-stage vibration isolation system.
Figure 7 to Figure 9 shows the comparison of results of example A1, A4 and A5. It can be found that the maximum acceleration of generator decreasing with the increasing of clearance of the upper elastic displacement limiter. Meanwhile, the maximum displacement of the upper vibration isolator becomes larger with the increasing of clearance of the upper elastic displacement limiter. The maximum displacement of the lower vibration isolator is decreasing slight. It is because that the resistance force received by the upper vibration isolator decreases with the increasing of the clearance of upper elastic displacement limiter.

Figure 7. Comparison of generator's acceleration of example A1, A4 and A5.

Figure 8. Comparison of upper vibration isolator's displacement of example A1, A4 and A5.

Figure 9. Comparison of lower vibration isolator's displacement of example A1, A4 and A5.
3.3. Analysis of the Influence of Using Lower Elastic Displacement Limiter on System Shock Response

In order to analysis the influence of using lower elastic displacement limiter on system shock response, five examples with different stiffness of lower elastic displacement limiter were set up. There are not upper elastic displacement limiter in these examples, and the clearance of lower elastic displacement limiter is 10 mm. The stiffness of the lower elastic displacement limiter is listed in Table 3. The shock response of examples B1-B5 were shown in Figure10 to Figure 12.

Table 3. Example of using lower elastic displacement limiter alone.

| Example ID | Stiffness of the lower elastic displacement limiter, $k_b$(N/m) | Clearance of the lower elastic displacement limiter, $D_b$(mm) |
|------------|---------------------------------------------------------------|-----------------------------------------------------------|
| B1         | $1.95\times10^7$                                              | 10                                                        |
| B2         | $2.4\times10^7$                                               | 10                                                        |
| B3         | $3.0\times10^7$                                               | 10                                                        |
| B4         | $1.95\times10^7$                                              | 15                                                        |
| B5         | $1.95\times10^7$                                              | 20                                                        |

Figure 10. Comparison of generator's acceleration of example B1, B2 and B3.

Figure 11. Comparison of upper vibration isolator 's displacement of example B1, B2 and B3.
Comparison the result of example B1 to B3, it can be found that the maximum acceleration of generator also increases with the increasing of stiffness of the lower elastic displacement limiter. With the increasing of stiffness of the lower elastic displacement limiter, the maximum displacement of upper vibration isolator is increasing. It is because the resistance force received by the upper vibration isolator increases with the increasing of the stiffness of lower elastic displacement limiter once the elastic displacement limiter works. The displacement of the upper vibration isolator becomes larger with the higher resistance force received by the upper vibration isolator. Meanwhile, the lower vibration isolator is difficult to deform due to the increasing of the stiffness of the lower elastic displacement limiter. Thus, the maximum displacement is decreasing with the increasing of the stiffness of the lower elastic displacement limiter.

Figure 13 to Figure 15 shows the comparison of results of example B1, B4 and B5. It can be found that the stiffness of the lower elastic displacement limiter has no obvious effect on the maximum displacement of upper and lower vibration isolator. This is because the maximum displacement of the vibration isolator appears in the previous reciprocating cycles. Even if the resistance force received by the lower vibration isolator increases with the increasing of the clearance of lower elastic displacement limiter, the maximum displacement of lower vibration isolator changes little due to the large stiffness of lower vibration isolator.

Figure 12. Comparison of lower vibration isolator’s displacement of example B1, B2 and B3.

Figure 13. Comparison of generator's acceleration of example B1, B4 and B5.
3.4. Influence of the Ratio of the Stiffness of Limiter to Vibration Isolator on System Shock Response

In order to analyse the influence of the ratio of the stiffness of lower elastic displacement limiter to lower vibration isolator on system shock response, there are six numerical examples to be compared. The stiffness of upper elastic displacement limiter is $1.0 \times 10^7$ N/m in these examples. The clearance of upper elastic displacement limiter is 5mm in these examples. The ratio of the stiffness of lower elastic displacement limiter to lower vibration isolator is listed in Table 4. The shock response of C1-C6 are shown in Figure 16-Figure 18. Based on the numerical results, it can be found that the maximum acceleration of generator and maximum displacement of upper vibration isolator increase with the increasing of the ratio of the stiffness of lower elastic displacement limiter to lower vibration isolator. It is because that the floating raft reciprocates under the shock load. When the stiffness of lower elastic displacement limiter become larger, due to the secondary shock load, the resistance force received by the lower vibration isolator is also increases. When the ratio of the stiffness of lower elastic displacement limiter to lower vibration isolator greater than 10, the maximum displacement decreases rapidly with the increasing of the ratio of the stiffness of lower elastic displacement limiter to lower vibration isolator. When the ratio of the stiffness of lower elastic displacement limiter to lower vibration isolator smaller than 10, due to the stiffness of vibration isolator and elastic displacement limiter is similar, the limiting effect of elastic displacement limiter is not obvious. Therefore, there are not significant change in the maximum displacement of lower vibration isolator.
Table 4. Parameters of example C1-C6.

| Example ID | Stiffness of the lower elastic displacement limiter, $k_b$ (N/m) | Stiffness of the lower vibration isolator, $k_2$ (N/m) | Clearance of lower elastic displacement limiter, $D_b$ (mm) | $k_b/k_2$ |
|------------|---------------------------------------------------------------|------------------------------------------------------|--------------------------------------------------------|----------|
| C1         | $4.0 \times 10^7$                                            | $1.9 \times 10^6$                                    | 10                                                     | 21.05    |
| C2         | $3.0 \times 10^7$                                            | $1.9 \times 10^6$                                    | 10                                                     | 15.79    |
| C3         | $2.4 \times 10^7$                                            | $1.9 \times 10^6$                                    | 10                                                     | 12.63    |
| C4         | $1.95 \times 10^7$                                           | $1.9 \times 10^6$                                    | 10                                                     | 10.26    |
| C5         | $1.25 \times 10^7$                                           | $1.9 \times 10^6$                                    | 10                                                     | 6.58     |
| C6         | $1.0 \times 10^7$                                            | $1.9 \times 10^6$                                    | 10                                                     | 5.26     |

**Figure 16.** Influence of the ratio of the stiffness of lower elastic displacement limiter to lower vibration isolator on generator’s acceleration.

**Figure 17.** Influence of the ratio of the stiffness of lower elastic displacement limiter to lower vibration isolator on upper vibration isolator displacement.
Figure 18. Influence of the ratio of the stiffness of lower elastic displacement limiter to lower vibration isolator on lower vibration isolator displacement.

4. Conclusions
Due to the limitation of the deformation capacity of the external pipeline of floating raft and the vibration isolators, installing elastic displacement limiter is an effective method to limit the displacement of equipment which installed on the floating raft. In this paper, according to the numerical research, some conclusions have been obtained.

(1) The shock response of the double-stage vibration isolation system is closely related to the parameters such as the stiffness and assembled clearance of elastic displacement limiter. Although the use of elastic displacement limiter can effectively limit the maximum displacement of the equipment, it also causes the maximum acceleration of equipment to increase.

(2) The stiffness of the lower limiter has a greater influence on the shock response of the double-stage vibration isolation system. With the increasing of the lower limiter stiffness, the maximum acceleration of equipment is linearly increasing, and the displacement of the lower isolators is decreasing rapidly. However, when the stiffness of lower limiter become too large, the equipment will be suffer a excessive secondary shock load which leads the equipment deformation increasing rapidly. it is harmful to equipment shock isolation.

5. References
[1] Junchuan N, Kongjie S and Lim CW 2005 On active vibration isolation of floating raft system Journal of Sound and Vibration, 285 391-406
[2] Dao-fu L, Yong-feng Y and Hong-xing H 2004 The shock response analysis of a raft isolation system with restrictors Noise and Vibration Control, 24 6-9
[3] Guohe J, Rongying S and Liguo Y 2006 Nonlinear shock response calculation of shipboard equipment with displacement restrictor using pseudo-force approach Journal of Ship Mechanics, 10 138-50
[4] Lu H, Xiansong M, Ming Y and He Z 2017 Calculation method of locking torque based on elastic thin shell theory for hydraulic locking sleeve. Marine Technology, 9 138-50
[5] Bing-jie M, Jianping S and Zhigang W 2011 Affect of displacement restrictor on shock resistance performance of double-stage vibration isolation system Noise and Vibration Control, 31 72-5
[6] Yinglong Z, Lin H and Yingyun H 2005 Influence of the displacement restrictor on shock resistance performance of vibration isolation system Journal of Vibration and Shock 24 71-6