SHOCK ISOLATION PERFORMANCE OF A NOVEL QUASI-ZERO STIFFNESS DISPLACEMENT RESTRICTOR

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In order to solve secondary shock problem of vibration isolator accompanied with traditional displacement restrictor, a novel Quasi-Zero stiffness displacement restrictor was developed based on Quasi-Zero stiffness isolation technology. An expression of force-displacement of the displacement restrictor is derived and its Quasi-Zero stiffness interval is optimized. The mathematic model of the shock isolation system with Quasi-Zero stiffness displacement restrict is established, and with the shock response of the equivalent linear shock isolation system with displacement restrict were compared. The results prove that in comparison with traditional linear shock isolation system with displacement restrict, the Quasi-Zero stiffness displacement restrictor can obviously reduce the absolute acceleration amplitude and achieve the approximate ideal of the rectangular buffer characteristics.

Keywords: Quasi-Zero stiffness; displacement restrictor; shock isolation; buffer coefficient

1. Introduction

The first step of anti-vibration and anti-shock design of marine equipment design is traditionally design of vibration isolation, then anti-shock check [1]. The vibration isolator, designed by the above idea, can reduce the amplitude of the absolute acceleration response of the equipment, but it will produce larger relative displacement amplitude, which may cause damage to the accessory piping of the equipment, or even exceed the ultimate deformation capacity of this vibration isolator [2]. For this reason, to ensure that the amplitude of acceleration response of the equipment does not exceed the allowable value, a displacement restrictor is installed in the vibration isolation system to limit the relative displacement amplitude of the device. However, if the selected parameter of the displacement restrictor is unreasonable, it will cause the secondary shock of the system. Therefore, it is necessary to optimize the design of the displacement restrictor.

Wen liuhan.Heisha et al [3] proposed the use of displacement restrictor to solve the problem of initial rigidity and yield strength in the two-way isolation railway bridge and the vehicle-bridge coupling dynamic response analysis. Xiang Xu et al [4] used nonlinear time-history analysis method to study the effect of displacement restrictor on the seismic performance of the bridge. The results showed that selecting the reasonable displacement restrictor parameters could effectively improve method to study the effect of the mounting clearance and stiffness of the elastic displacement restrictor on the shock resistance of the double-layer vibration isolator. Ma Bingjie et al. [5] used the finite element method to study the effect of the mounting clearance and stiffness of the elastic displacement restrictor on the shock resistance of the double-layer vibration isolator. Weng Xuetao et al. [6] Calculated the impulse responses of the rigid displacement restrictor and the damping restrictor impulse system under the step velocity shock and analysed the influence of parameters. Smith Tang et al. [7] used the finite element method and genetic algorithm to optimize the design, and obtained the optimal solution set of the stiffness segmented linear isolation system. Based on the one-way constrained multi-body dynamics theory, Zhang Chunhui et al. [8] solved the dynamic equation of the double displacement restrictor shock isolation system by using the segmented Duhamel integral, and analysed the influence of the design parameters of the restrictor on the impulse response. And the multi-island genetic algorithm was used to optimize the limiter parameters. However, research [1; 9] have shown that the ideal impulse response curve should be approximately rectangular. The above research provides a theoretical basis for the practical application of the displacement restrictor in the seismic isolation and vibration isolation of the bridge, but neither can achieve the ideal rectangular cushioning characteristic.

Quasi-Zero stiffness isolation technology is an emerging low-frequency vibration isolation technology, having the characteristic that the stiffness is approximately zero within the specified range. In other words, force-displacement curve of displacement restrictor is approximately rectangular. The theory and experiment of this technique in the field of low frequency vibration isolation have been extensively studied, but is rarely studied in the field of shock isolation. Carrella A et al [10] conducted a static stiffness analysis of a passive vibration isolator consisting of a vertical spring and two inclined springs. Kovacic I and Carrella A et al [11;12] obtained the Quasi-Zero stiffness isolator by parametric modeling and optimization design, and simplified the Quasi-Zero stiffness isolator model into Duffing equation to solve the system response. In this study, a novel displacement restrictor is designed based on the zero-stiffness structure of the inclined spring, which combining gap limit technique and Quasi-Zero stiffness isolation technique. It is expect to realize the ideal rectangular buffer characteristic.

2. Composition of Quasi – Zero Stiffness Displacement Restrictor

The simplified structure of displacement restrictor with Quasi-Zero stiffness characteristic is shown in Figure 1. The displacement restrictor mainly comprises a shock head 1 for limit the displacement, and the lower end is connected to the plurality of Oblique springs 5 and the vertical springs 4, and the upper ends are fixed in the outer shell 3 by the upper cover 2. The vertical spring 4 and a plurality of Oblique springs 5 are connected in parallel to form an elastic element, which having a Quasi-Zero stiffness characteristic. There is a certain preload F0 in the initial position of the displacement restrictor to prevent the pre-tightening force to push the shocking head 1 upward, and the upper cover 2 is pressed and fixed inside the outer shell 3.

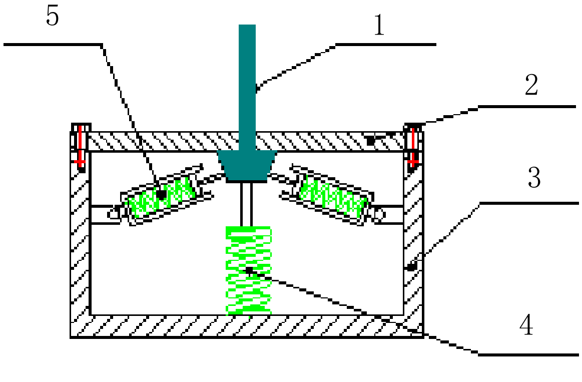

Fig. 1 The structure of displacement restrictor with Quasi-Zero stiffness characteristic

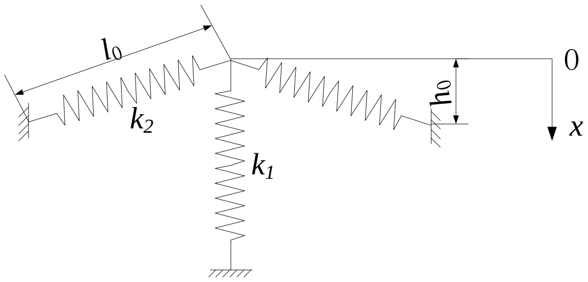

Fig. 2 The diagram of displacement restrictor with Quasi-Zero stiffness characteristic

3. Static Analysis

Quasi-Zero stiffness displacement restrictor works as shown in Figure 2.The coordinates *O*-*x* is established, the stiffness of the Oblique spring is k_2, the initial compression is l_{01}, the initial position length is l_0, the vertical height of the tilt is h_0, the vertical spring stiffness is k_1, the initial compression is x_0, The initial position of the vertical spring and the Oblique spring to provide the elastic force are:

$$F_1 = -k_1 x_0 \tag{1}$$

$$F_2 = -k_2 l_{01} \tag{2}$$

The shocking head 1 moves downwardly *x*, and the elastic force of the vertical spring becomes:

$$F_1 = -k_1\left(x_0 + x\right) \tag{3}$$

The length of the oblique spring becomes:

$$l_1 = \sqrt{\left(l_0{}^2 - h_0{}^2\right) + \left(h_0{}^2 - x^2\right)} \tag{4}$$

The inclination angle of the oblique spring and the horizontal direction becomes:

$$\sin\theta = \frac{h_0 - x}{l_1} \tag{5}$$

The spring force of the Oblique spring becomes:

$$F_2 = -k_2\left(l_0 + l_{01} - l_1\right) \tag{6}$$

The vertical Component of the elastic force of the oblique spring is:

$$F_{2c} = -k_2\left(h_0 - x\right)\left(\frac{l_0 + l_{01}}{\sqrt{\left(l_0{}^2 - h_0{}^2\right) + \left(h_0{}^2 - x^2\right)}} - 1\right) \tag{7}$$

The total vertical force of the displacement restrictor

$$F = -k_1\left(x_0 + x\right) - nk_2\left(h_0 - x\right)\cdot\left(\frac{l_0 + l_{01}}{\sqrt{\left(l_0{}^2 - h_0{}^2\right) + \left(h_0 - x\right)^2}} - 1\right) \tag{8}$$

Where, *n* is the number of Oblique springs for each displacement restrictor.

The dimensionless variables are introduced:

$$F' = \frac{F}{k_1 h_0}, \quad x' = \frac{x}{h_0}, \quad x_0{}' = \frac{x_0}{h_0}, \quad l_0{}' = \frac{l_0}{h_0}, \quad l_{01}{}' = \frac{l_{01}}{h_0}, \quad a = \frac{k_2}{k_1} 。$$

Bring the above-mentioned non-dimensional variables into the formula (8),can be obtained the dimensionless expression of the vertical elastic force of displacement restrictor:

$$F' = -\left(x'_0 + x'\right) - na\left(1-x'\right)\cdot\left(\frac{l'_0 + l'_{01}}{\sqrt{\left(l_0'^2 - 1\right) + \left(1-x'\right)^2}} - 1\right) \tag{9}$$

For the derivative of the formula (9), the dimensionless expression of the vertical stiffness of displacement restrictor is obtained:

$$k' = na\left[\frac{l_0' + l_{01}'}{\sqrt{(x'-1)^2 + l_0'^2 - 1}} - \frac{(x'-1)^2 (l_0' - l_{01}')}{\left(l_0'^2 + x^2 - 2x\right)^{3/2}} - 1\right] - 1 \tag{10}$$

The derivative of the formula (10) is obtained:

$$\frac{\partial k'}{\partial x} = \frac{-6a(l_0{}^2 - 1)(l_0 + l_{01})(x-1)}{\left(l_0{}^2 + x^2 - 2x\right)^{5/2}} \tag{11}$$

Let (11) be zero, and the displacement extremum of the Quasi-Zero stiffness displacement restrictor is $x = 1$, Let $x=1$ into the formula (10) and let k'=0 to get the condition that the displacement restrictor takes zero stiffness at the extreme position:

$$a = \frac{1}{n\left(\frac{l_0' + l_{01}'}{\sqrt{l_0'^2 - 1}} - 1\right)} \tag{12}$$

Bring (12) into the (9) and (10), obtain:

$$F' = -\left(x'_0 + x'\right) - \frac{1}{\left(\frac{l_0' + l_{01}'}{\sqrt{l_0'^2 - 1}} - 1\right)}\cdot\left(1-x'\right)\left(\frac{l'_0 + l'_{01}}{\sqrt{\left(l_0'^2 - 1\right) + \left(1-x'\right)^2}} - 1\right) \tag{13}$$

$$k' = \frac{1}{\left(\frac{l_0' + l_{01}'}{\sqrt{l_0'^2 - 1}} - 1\right)}\left(\frac{l_0' + l_{01}'}{\sqrt{(x'-1)^2 + l_0'^2 - 1}} - \frac{(x'-1)^2 (l_0' - l_{01}')}{\left(l_0'^2 + x^2 - 2x\right)^{3/2}} - 1\right) - 1 \tag{14}$$

It can be seen from (13) and (14) that the non-dimensional expression of the vertical elastic force and vertical stiffness of the Quasi-Zero stiffness displacement restrictor is a function of the non-dimensional displacement(x_0'). The vertical elastic force is affected by the variables x_0' 、 l_0' 、 l_{01}', the stiffness of the displacement restrictor is only affected by l_0', l_{01}'.

4. Parametric Effect Analysis of Quasi - zero-Stiffness Displacement Restrictor

4.1 Influence of Geometric Parameters l_0' and l_{01}' o on Stiffness characteristics of displacement restrictor

In order to maintain the spring force of the restrictor approximately constant, a broad dimensionless displacement range x_q' . In this range, the stiffness of the restrictor is less than the set threshold k_q', Suppose $x'_{k'=k_q'} = x_q'$, and into the formula (14) can be obtained :

$$\frac{1}{\left(\frac{l_0'+l_{01}'}{\sqrt{l_0'^2-1}}-1\right)}\left[\frac{l_0'+l_{01}'}{\sqrt{(x_q'-1)^2+l_0'^2-1}}-\frac{(x_q'-1)^2(l_0'-l_{01}')}{\left(l_0'^2+x_q'^2-2x_q'\right)^{3/2}}-1\right]-1-k_q'=0 \tag{15}$$

Obviously, equation (15) has no explicit analytic solution, so we use numerical simulation method to find the optimal geometric parameters. Set the relevant parameters of the range: The specific optimization method is to make $k_q'=0.01$($k_q'=1$ means that the stiffness of the displacement restrictor in this position is the stiffness k_1 of the vertical spring), using Matlab software programming to find each design parameter, So that k' is approximately equal to the displacement value x_q' of k_q'. Numerical simulation results shown in Figure 3.It can be seen that the larger l_0', l_{01}', then the larger the x_q'c, that is, the wider the range of Quasi-Zero displacement range. Therefore, in the displacement restrictor design, in the space allowed, should try to choose a larger l_0', l_{01}'.

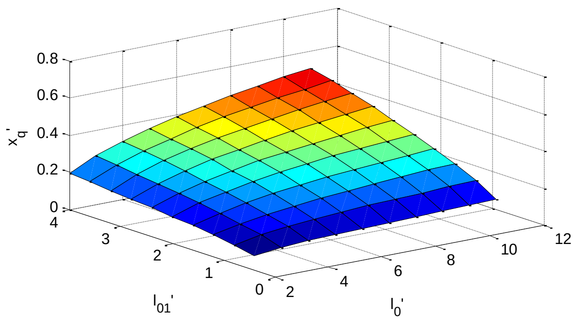

Fig. 3 Optimization Results of Design Parameters for QZS displacement restrictor

4.2 Influence of geometric parameters x_0', l_0' and l_{01}' on force - displacement characteristics of displacement restrictor

The other parameters remain unchanged，Change the parameters x_0', l_0' and l_{01}', and study these three parameters on the displacement restrictor. It can be seen, $l_0'$and l_{01}'increases, Quasi-Zero stiffness displacement restrictor F'-x 'curve becomes more gentle, vertical elastic force is more similar to constant force. x_0' Increases, F'-x 'curve parallel rise, since x_0' has no effect on the stiffness properties. Therefore, changing x_0', without prejudice to the premise of the stiffness characteristics of the displacement restrictor, to change the preload of the displacement restrictor.

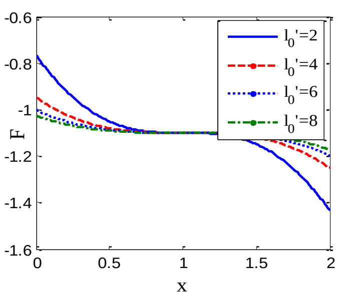

Fig. 4 Effect of l_0' to F'-x' curves

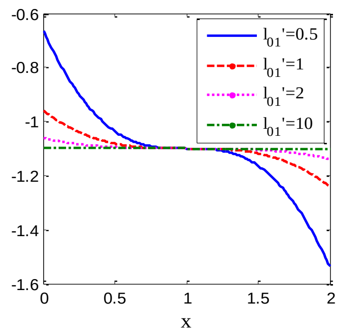

Fig. 5 Effect of l_0' to F'-x' curves

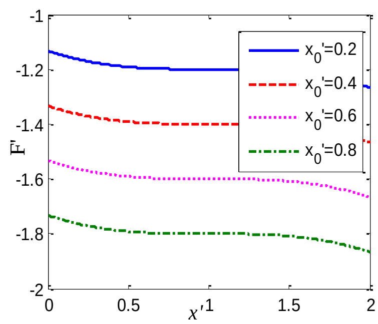

Fig. 6 Effect of x_0' to F'-x' curves

5. Dynamic response of the shock isolation system with Quasi-Zero stiffness displacement restrictor

A shock isolation system with a Quasi-Zero stiffness displacement restrictor is shown in Figure 7. Assuming that the bases of the system by the shock signal $\ddot{y}(t)$, so that the relative displacement $\delta = x - y$, according to Newton's second law, the system can be listed differential equations of motion:

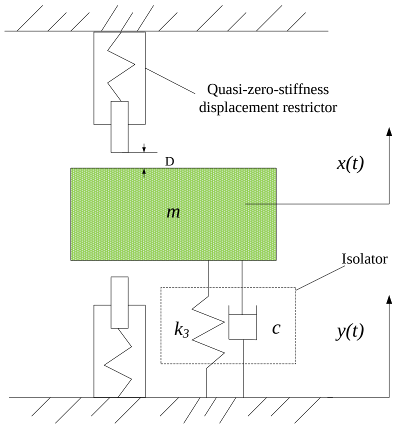

Fig. 7 Simplified model of the shock isolation system with QZS displacement restrictors

$$\begin{cases} \mathrm{m}\ddot{\delta}(t) + c\dot{\delta}(t) + k_3\delta(t) = -m\ddot{y}(t) & (|\delta(t)| \le D) \\ \mathrm{m}\ddot{\delta}(t) + c\dot{\delta}(t) + k_3\delta(t) + F_{DR} = -m\ddot{y}(t) & (\delta(t) > D) \\ \mathrm{m}\ddot{\delta}(t) + c\dot{\delta}(t) + k_3\delta(t) - F_{DR} = -m\ddot{y}(t) & (\delta(t) < -D) \end{cases} \tag{16}$$

Where F_{DR} is the elastic force F of the restrictor and the expression is given by equation (8);

For the shock excitation $\ddot{y}(t)$, according to the German military standard BV043-85 [13] recommended positive and negative half-sinusoidal time domain signal selection, the specific expression is:

$$\ddot{y}(t) = \begin{cases} a_2 \sin(p_1 t) & 0 < t < t_1 \\ -a_4 \sin p_2(t - t_1) & t_1 \le t < t_2 \\ 0 & t_2 \le t \end{cases} \tag{17}$$

where $a_2 = 0.5A_0$, $t_1 = \frac{\pi \cdot V_1}{2 \cdot a_2}$, $V_1 = \frac{2}{3} \cdot V_0$, $a_4 = \frac{\pi \cdot V_1}{2 \cdot (t_2 - t_1)}$, $t_2 = \frac{2 \cdot d_0}{V_1}$, $p_1 = \frac{\pi}{t_1}$, $p_2 = \frac{\pi}{t_2 - t_1}$ 。

According to the BV043-85 standard, the corresponding spectrum values of the elastic device are acceleration spectrum value = 320 *g*, velocity spectrum value = 7 *m / s*, displacement spectrum value = 43 *mm*.

Assuming that the isolation device can withstand the amplitude of the acceleration A_0, can withstand the relative displacement amplitude x_r, the pre-tightening force of the restrictor F_0 is:

$$F_0 = m(A_0 + \varepsilon) - k_3 x_r \tag{18}$$

Where, ε is a minimum value less than zero.

According to the optimization results in Section 4.1, when the geometric parameter *h* is constant, choose the largest possible l_0 and l_{01}. According to the parameters of section 4.2, select the appropriate initial compression x_0 for the vertical spring.

6. Contrast with linear system

In order to verify the buffer restrict effect of the Quasi-Zero stiffness restrictor, a practical restrictor parameter was designed according to the above study. The restrictor parameters are shown in Table 1.

Tab.1 the parameters of QZS displacement restrictor

k_1 (N/m)	k_2 (N/m)	h_0 (m)	l_0 (m)	l_{01} (m)	x_0 (m)
1.8e+005	2.1e+005	0.0250	0.1250	0.0500	0

In order to study the advantages and disadvantages of Quasi-Zero stiffness displacement restrictor more clearly, Using energy efficiency equivalence [7],the equivalent linear stiffness, which is the same as the dissipated energy of the Quasi-Zero stiffness displacement restrictor, is obtained as the stiffness of the linear restrictor, with the value of 252.35KN/m. The shock response of the linear restrictor and the shock isolation system with Quasi-Zero stiffness displacement restrictor is shown in Fig. 8 and Fig. 9 when the same shock excitation is applied. It can be seen that although the relative displacement amplitude of the shock isolation system with Quasi-Zero stiffness displacement restrictor is slightly larger than that of the linear displacement restrictor, but the acceleration response amplitude of the former(10.4g) is significantly smaller than the latter's acceleration response amplitude (20.4g) Therefore, the shock isolation system with Quasi-Zero stiffness displacement restrictor can reduce the amplitude of the absolute acceleration response and increase the shock resistance of the whole system on the basis of the slight increase of relative displacement amplitude.

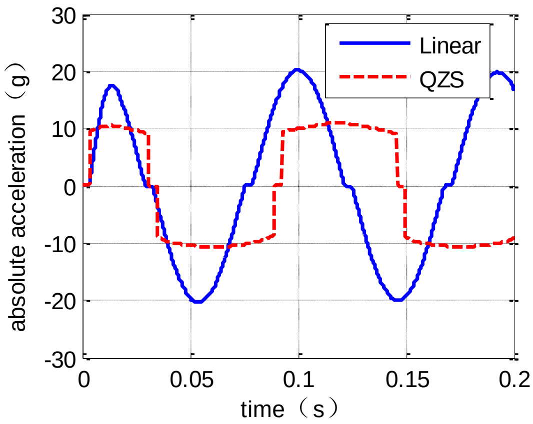

Fig. 8 Absolute acceleration responses of two kinds of different displacement restrictor system

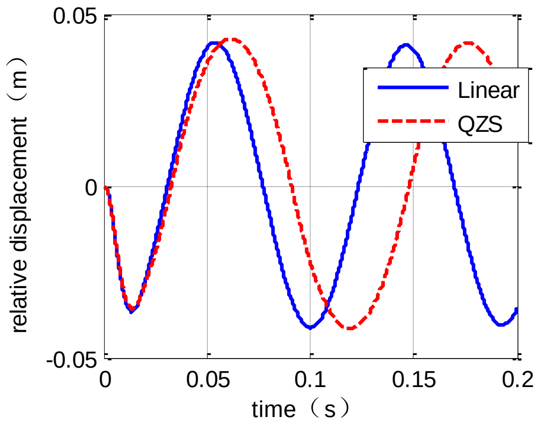

Fig. 9 Relative displacement responses of two kinds of different displacement restrictor system

7. Conclusions

Based on the optimal anti-shock theory, a novel Quasi-Zero stiffness displacement restrictor is proposed and the force-displacement relation of the restrictor is deduced. The influence of the design parameters of the restrictor on its mechanical properties is analyzed, and its stiffness characteristics were optimized. At the same time, the dynamic model of the shock isolation system with Quasi-Zero stiffness displacement restrictor is established and compared with the linear displacement restrictor system . The main conclusions are:

(1) The larger the dimensionless parameter l_{01}' of the restrictor, the larger the Quasi - Zero stiffness range of the Quasi-Zero stiffness displacement restrictor, the more gentle the non-dimensional force-displacement curve, and the vertical elastic force is more constant.

(2) Change the vertical dimension of the initial compression x_0' of the spring, without affecting the Quasi-Zero stiffness characteristics of the restrictor, can change the preload force value of the restrictor;

(3) Compared with the shock isolation system with linear restrictor, the shock isolation system with Quasi-Zero stiffness displacement restrictor can effectively reduce the system's absolute acceleration response amplitude and achieve the approximate ideal of the rectangular buffer characteristics.

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