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Research Article

The Shock Response Spectrum of Two Degree-of-Freedom System Dropping on the Expandable Polyethylene Pad

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Abstract: The shock response spectrum of the system with a key component dropping on the extruded polyethylene pad was investigated since the expandable polyethylene is widely used in packaging system and dropping damage is occurred usually. And the effect of nominal frequency ratio, damping ratio, mass ratio and the amplitude of the to the shock response spectrum of the key component and the main part were discussed; these concepts and the results have important value in the design of cushioning packaging.

Keywords: Expandable polyethylene pad, frequency ratio, key component, shock response spectrum

INTRODUCTION

The main causes for damage of package system are vibration and dropping during transportation and the key component always be damaged at the first, so it is more precision to predigest the packaged products as an two-degree-of-freedom system (Jiang and Wang, 2004). Shock response spectrum is an important base to evaluate the reliability of cushioning Wang (2001) has studied shock response spectrum and damage boundary curve of single degree-of-freedom system under different pulsed excitation, Jiang and Wang, (2008) has proposed the concept of three-dimensional shock spectrum and damage boundary surface with tangent system. Since the Expandable Polyethylene (EPE) (Wang, 2002) is widely used in packaging system for its better cushioning properties and the dropping damage is always occurred, so this study will investigate the shock response spectrum of both main body and key component of two-degree-of-freedom system dropping on the expandable polyethylene pad and discuss the effects of nominal frequency ratio, damping ratio as well as mass ratio (Wang and Wang, 2008).

DROPPING IMPACT EXPERIMENT

The impact dynamic response was experiments were carried out with the shock facility (CL-100, Suzhou, China) is shown in Fig. 1, the acceleration response of the platform was recorded is shown in Fig. 2, by applying Matlab curve fitting, the shock wave shape of the platform drooping on the EPE pad was fitted as bell shaped impulse function. The EPE was produced by Saiweike Limited Company Wuhan.

Fig. 1: Test-bed of dropping impact system

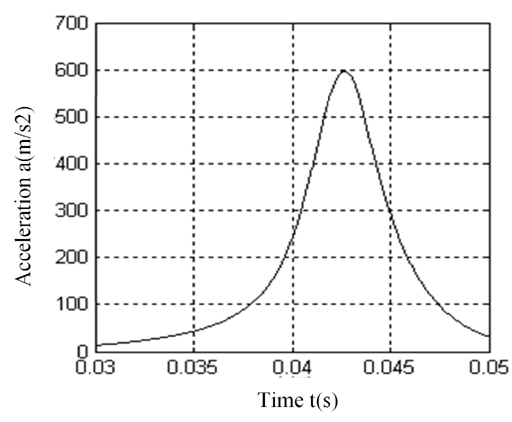

Fig. 2: Measure curve of acceleration response

Experiment parameter as follows: the density is ρ = $0.0030 g/cm^2$, thickness is d = 40mm, length and width is

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l = 200mm.The sampling frequency of acceleration transducer is 2400Hz. Dropping height is H = 410mm.

MODELING AND NON-DIMENSIONAL EQUATIONS

According the experiment, the shock wave shape is the same, but the amplitude and pulse width are different when the dropping height and expandable polyethylene's thickness are changed. By applying curve fitting, the shock wave shape is similar the bell shaped pulse. The paper studied dynamics response characteristic of the system under the bell shaped pulse in widely meaning as shown in Fig. 3, the function is $\ddot{u} = u''_{0m} e^{-(\frac{t}{t_0})^2} \Delta H(t, t_0)$. The dynamic model of packaging system with a key component is shown in Fig. 4, where m_1 and m_2 are the mass of key component and main part respectively, k_1 and c_1 are the equivalent linear elasticity coefficient and equivalent damping ratio of the two parts, k_2 and c_2 are the linear elastic coefficient and damping ratio of cushioning material respectively.

The differential equations of two degree-of-freedom system under preceding peak saw tooth pulse can be written as:

$$\begin{cases} m_1 \ddot{x}_1 = k_1(x_2 - x_1) + c_1(\dot{x}_2 - \dot{x}_1) \\ m_2 \ddot{x}_2 = k_2(u - x_2) + c_2(\dot{u} - \dot{x}_2) + \\ \qquad k_1(x_1 - x_2) + c_1(\dot{x}_1 - \dot{x}_2) \end{cases} \quad (1)$$

Non-dimensional displacement and time were introduced:

$$X = \frac{x-u}{L}, U = \frac{u}{L}, \tau = \frac{t}{T}, T = \sqrt{\frac{m_2}{k_2}}$$

and define:

$$\zeta_1 = \frac{c_1}{2\sqrt{m_1 k_1}}, \quad \zeta_2 = \frac{c_2}{2\sqrt{m_2 k_2}}$$

$$\alpha = \frac{m_1}{m_2}, \quad \lambda = \frac{\omega_1}{\omega_2}, \omega_1 = \sqrt{\frac{k_1}{m_1}}, \omega_2 = \sqrt{\frac{k_2}{m_2}}$$

where X\`and X\`\` are first derivative and second derivative respectively. Applied a preceding peak saw tooth acceleration pulse excitation on the base and the non-dimensional equation is:

$$\begin{cases} X''_1 = \lambda^2(X_2 - X_1) + 2\lambda\zeta_1(X'_2 - X'_1) - U'' \\ X''_2 = -X_2 + \lambda^2\alpha(X_1 - X_2) + \\ \qquad 2\zeta_1\lambda\alpha(X'_1 - X'_2) - 2\zeta_2 X'_2 - U'' \end{cases} \quad (2)$$

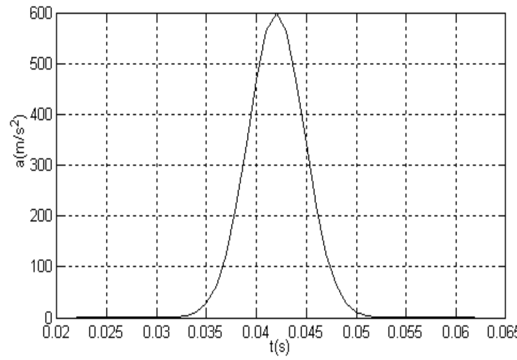


Fig. 3: Bell shaped impulse

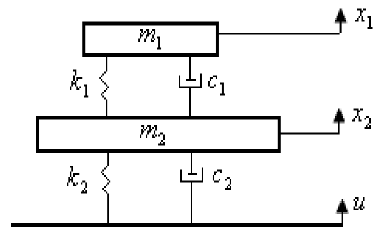


Fig. 4: Dynamic model of two degree-of-freedom system

$$U'' = U''_{0m} \Delta H(\tau, \tau_0)$$

where,

U''_{0m} = The amplitude

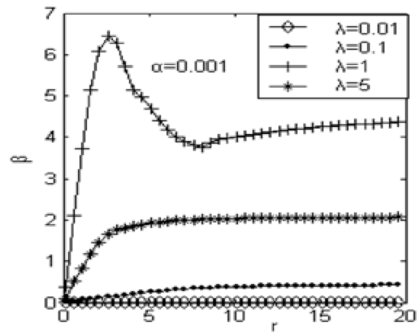
τ_0 = The width of the bell shaped acceleration pulse

$$\ddot{U} = \begin{cases} U''_{om} e^{-(\frac{\tau}{\tau_0})^2} & (-\tau_0 \le \tau \le \tau_0) \\ 0 & (|\tau| \ge \tau_0) \end{cases} \quad (3)$$

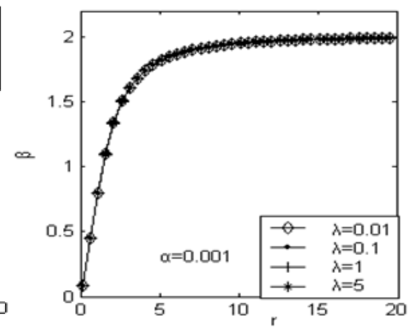
According to Eq. (2) and (3), the factors that influence the maximum value of acceleration response are: mass ratio, nominal frequency ratio, damping ratio of the main body and key component as well as impact time τ_0.

SHOCK RESPONSE SPECTRUM OF MAIN PART AND CRITICAL ELEMENT

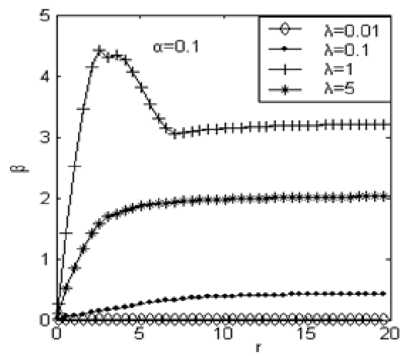
In order to evaluate the damage of the product during transportation, the maximum shock response spectrum is usually chosen to describe the response of the product on the impulse. Eq. (1) and (2) generally discussed shock response spectrum of two-degree-of-freedom system, thus the fourth order Runge-Kutta method is applied. The mass ratio is much smaller than 1 due to the simplification of packaging system, here the mass ratios are α = 0.001, 0.001, 0.1, 0.8, frequency



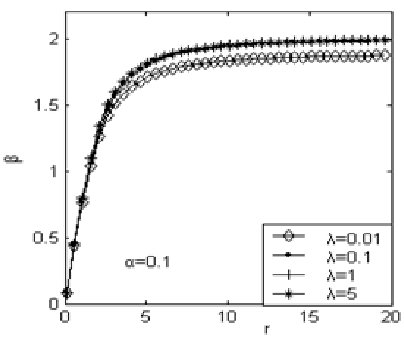
(a) SRS of key component



(b) SRS of the main body

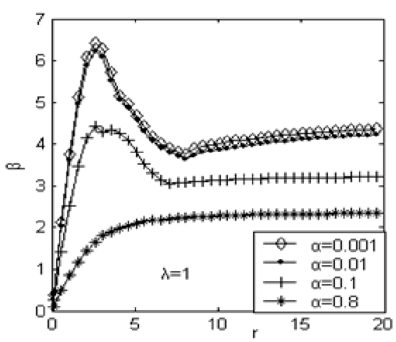


(c) SRS of key component

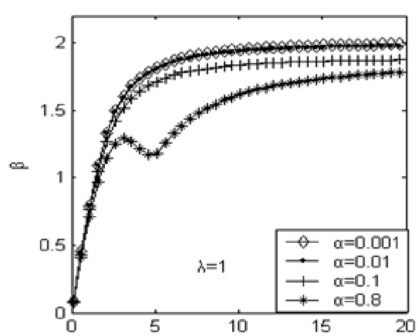


(d) SRS of the main body

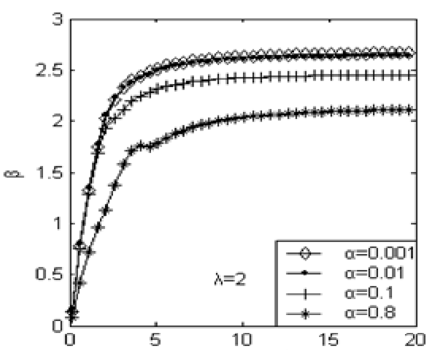
Fig. 5: SRS for packaging system with different frequency ratio ($\zeta 1 = 0$, $\zeta 2 = 0$)



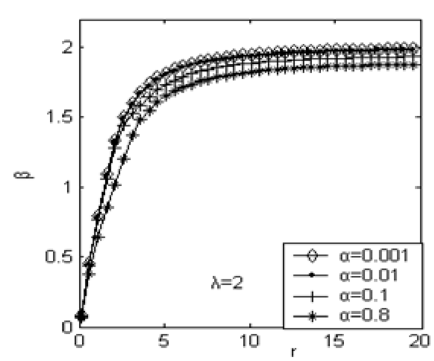
(a) SRS of key component



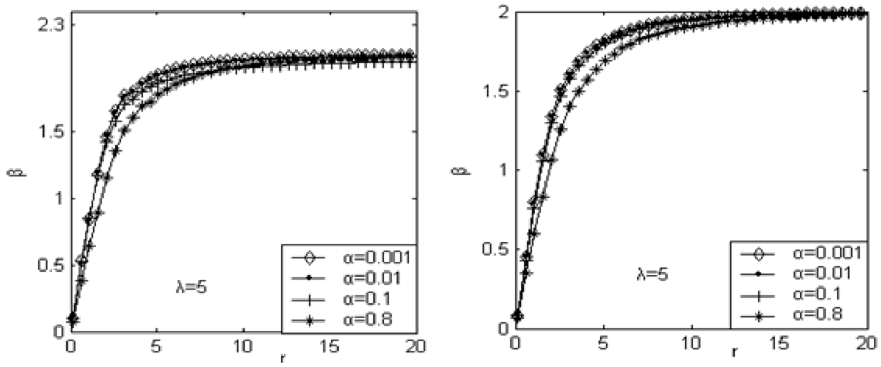
(b) SRS of the main body



(c) SRS of key component

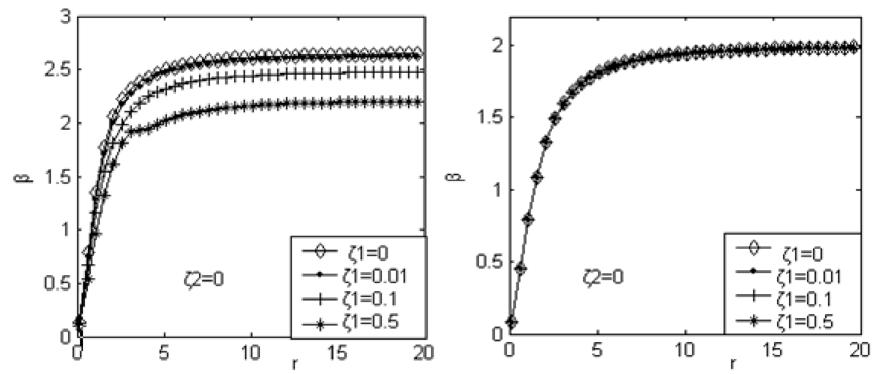


(d) SRS of the main body

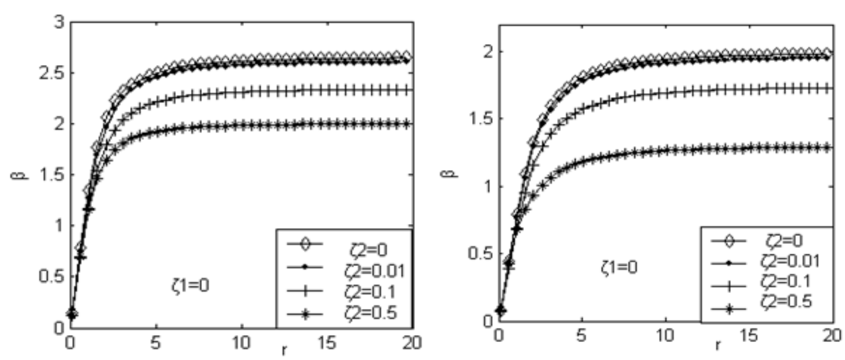


(e) SRS of key component (f) SRS of the main body

Fig. 6: SRS for packaging system with different mass ratio (ζ1= 0, ζ2 = 0)



(a) SRS of key component (b) SRS of the main body



(c) SRS of key component (d) SRS of the main body

Fig. 7: SRS for packaging system with different damp ratio (α = 0.1, λ = 2)

ratios are λ = 0.01, 0.1, 1, 5 and damping ratios are ζ1 = ζ2 -0 0 .01, 0.1, 0.5 respectively in order to compare the other impulse.

Since the shock response spectrum of two -degree-of-freedom system is a three-dimensional surface, the projection to the planes 2π f_0 t_0 – $\ddot{X}_{1m}/\ddot{U}_m$ and 2π f_0t_0-$\ddot{X}_{2m}/$ to investigate the effect of each parameter clearly, where r = f_{n2}/f_0, β = $_{xm}/\ddot{U}_{0m}$.

DISCUSSION OF THE RESULTS

Figure 5a to d indicates the effect of frequency ratio on the shock response spectrum. It is found that nominal frequency ratio has great impact on shock response spectrum of the key component, the response is also influenced by mass ratio, the amplitude of the response spectrum decrease as the mass ratio increasing (except = 1). But frequency ratio and mass ratio have little effect to the shock response spectrum of main body, it is almost the same as the single degree-of-freedom linear system, which decreases gradually after peak value and finally tends to 2.

Figure 6a to f shows the effects of mass ratio on the shock spectrum. It is shown that mass ratio has visible influence on the shock response spectrum of key component especially when the nominal frequency ratio nearly 1; as for the main body is small influence mainly because the mass of key component is much smaller than main body, thus the impact of key component to the main body could be neglected while frequency ratio is much smaller than 2; while frequency ratio is much bigger than 2, response spectrums of main body and critical element are almost the same, the response spectrums move upward as mass ratio increasing, while frequency ratio is approximate to 2, the response of key component increases as mass ratio decreasing and it has very little influence on main body. When $\lambda = 1$, the response spectrum of the key component is much bigger than the other cases, so this case should be avoided in the packaging design.

Fig. 7a to d shows the effect of damping ratio on the shock spectrum. The key component damping ratio that connecting the main body and key component could effectively reduce shock response spectrum and has little influence on main body of the product, while the damping ratio of the main body (cushioning material) could sharply reduce the shock response of critical element. These two damping ratios have the same influence on critical element, the shock response of main body decreases as damping ratio increasing.

CONCLUSION

- The shock response spectrum of two degree-of-freedom system under bell shaped impulse is directly related with mass ratio, nominal frequency ratio without coupling, damping ratio of main body and key component, as for EPE, these parameters are related with its characteristic
- The shock response spectrum does not rely on the peak value of shock wave, for the system is linear simplified and the response spectrum is almost the same as that of single degree-of-freedom system because in the packaging system, mass ratio of main body to key component is much smaller than 1, therefore, the impact could be neglected:
- The response of key component reaches the summit while non-coupling frequency ratio is around 4, so that it could be reduced by choosing cushioning materials to adjust the nominal frequency ratio in cushioning package design
- Damping ration could effectively reduce the response amplitude, thus it can be fully used in the cushioning packaging design.

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