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Analysis of energy dissipated by damping for paper honeycomb sandwich plate-block system

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Abstract

The vibration transmissibility of paper honeycomb sandwich plate was tested and the vibration transmissibility curve was simplified and characterized. Based on the basic principle of vibration mechanics, the equation for calculating the energy dissipated by damping of paper honeycomb sandwich plate-block system during vibration was deduced. Furthermore, the effects of honeycomb structural parameters (cell length, sandwich plate thickness) and block mass on the damping energy dissipation were analyzed. The results showed that the curves of vibration transmissibility for paper honeycomb sandwich plate can be divided into three regions: plateau region, amplification region, and attenuation region. The vibration transmissibility ratio in different regions can be expressed as functions of frequency. The energy dissipated by damping of paper honeycomb sandwich plate-block system depends on its vibration transmissibility. If the vibration transmissibility ratio–frequency curve is obtained, the damping energy dissipation of the system can be calculated. The total energy dissipation of paper honeycomb sandwich plate-block system during vibration is about equal to that of plateau region, and the energy dissipated in amplification and attenuation region can be neglected. Different honeycomb structural parameters have the same effect on the damping energy dissipation of the system. Block mass has little effect on the damping energy dissipation in plateau region and the total energy dissipation during vibration but has a greater impact on the energy dissipation in the amplification and attenuation regions. The purpose of this paper is to provide a basic method for calculation of energy dissipated by damping and evaluation of anti-vibration property for packaging material.

Keywords

Paper honeycomb sandwich plate, energy dissipated by damping, packaging system, structural parameters, mass of block

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Introduction

Paper honeycomb sandwich plate is an environment-friendly cushioning packaging material. The porous structure of honeycomb makes it have the advantages of light weight, high specific stiffness and strength, and stable energy absorption property. It is an effective packaging material to replace foam plastic.[1–5]

The cushioning property of packaging material mainly depends on the energy absorption during compression, while the anti-vibration property mainly depends on the damping energy dissipation during vibration. Scholars have done a lot of research on the cushioning property of paper honeycomb sandwich plate, including the construction of two-dimensional and three-dimensional energy absorption diagram,[6–8] which provides theoretical guidance for the selection and optimization of packaging design. While the anti-vibration property is relatively weak, which mainly involved the experiment of vibration transmissibility,[9,10] theoretical modeling of vibration transmissibility ratio[11] and finite element simulation analysis.[12] These studies mainly focus on the qualitative analysis of vibration transmissibility ratio and resonance frequency, while there is a lack of studies that deal with a quantitative evaluation of damping

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energy dissipation of paper honeycomb sandwich plate-block system. However, the evaluation and calculation of damping energy dissipation are of great significance in the optimization design of anti-vibration packaging. So it is necessary to explore the evaluation method of damping energy dissipation of paper honeycomb sandwich plate.

The main purpose of this paper is to simplify and characterize the vibration transmissibility curve of paper honeycomb sandwich plate, further derive the calculation of energy dissipation for paper honeycomb sandwich plate-block system based on the basic principles of vibration mechanics, and analyze the influence rule of honeycomb structural parameters (honeycomb cell length and sandwich plate thickness) and block mass on the damping energy dissipation of the system.

Experimental methods of vibration transmissibility for paper honeycomb sandwich plate

Referring to GB/T 8169-2008 and ASTM D3580-95(2015), the sinusoidal sweep experiment of paper honeycomb sandwich plate-block system was carried out. The experimental instrument is DC-300-3 electric vibration experimental system (made by Suzhou Sushi Testing Instrument Co., Ltd, China.) (see Figure 1). The system consists of vibration table, RC-2000 digital controller, power amplifier, acceleration sensors, and computer software. It can search the resonance point of the sample automatically, which stands for the peak value on the vibration transmissibility curve. The logarithmic sweep mode was adopted, the sweep rate was 1 Oct/min, the sweep range was 5–500 Hz, and the acceleration peak of target spectrum was 0.5 g.

Five kinds of paper honeycomb sandwich plate samples are selected. The base paper is corrugated paper, and the liner is Kraft. The size of samples is 200×200 mm^2. The material and structural parameters of the samples are shown in Table 1, G_1 stands for the grammage of liner and t_1 stands for the thickness of liner. G_2 stands for the grammage of base paper and t_2 stands for the thickness of base paper. All the samples were numbered by Sl/T in which l is honeycomb cell length and T is the thickness of sandwich plate (Figure 2). For example, S10/20 indicates the paper honeycomb sandwich plate samples with cell length of 10 mm and sandwich plate thickness of 20 mm. The vibration transmissibility of five kinds of specimens under four blocks (mass is 12.85 kg, 16 kg, 20.85 kg, and 24 kg) was tested. It should be noted that the size of block is 200×200 mm^2, and the mass is changed by height. The experiments were numbered by Sl/T-Mm in which Sl/T is the number of sample and m is the mass of block. For example, S10/20-16 indicates the vibration transmissibility experiment with sample number of S10/20 under block of 16 kg.

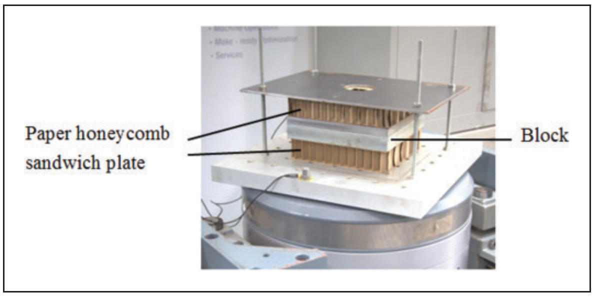

Figure 1. The experimental test system of vibration transmissibility for paper honeycomb sandwich plate-block system.

Table 1. Material and structural parameters of experimental samples.

Number	G_1 (g/m^2)	t_1 (mm)	G_2 (g/m^2)	t_2 (mm)	l (mm)	T (mm)
S6/20	230	0.3	110	0.17	6	20
S8/20	230	0.3	110	0.17	8	20
S10/20	230	0.3	110	0.17	10	20
S10/30	230	0.3	110	0.17	10	30
S10/40	230	0.3	110	0.17	10	40

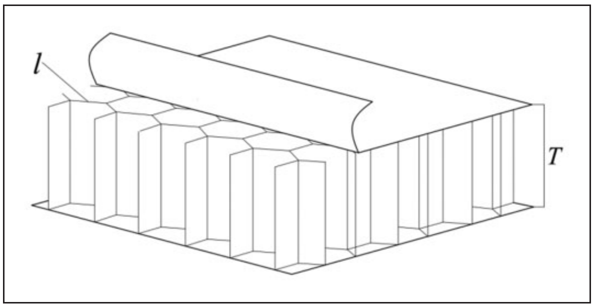

Figure 2. Structural factors of paper honeycomb sandwich plate.

Simplification and characterization of vibration transmissibility curve for paper honeycomb sandwich plate

Experiments show that the typical vibration transmissibility curve of paper honeycomb sandwich plate is seen in Figure 3(a), which could be divided into four zones: plateau region, amplification region, fluctuation region, and attenuation region. Due to the randomicity of peak and frequency in the fluctuation region, it was ignored in this paper, so the vibration transmissibility curve of paper honeycomb sandwich plate could be simplified, as shown in Figure 3(b). In the picture, f_0 is the starting point of sweep, f_1 is the starting point of the amplification area, f_2 is the terminal point of the amplification area, and the f_3 is the terminal point of sweep. The resonance point P denotes that resonance occurs near this frequency value. The abscissa of this point is resonance

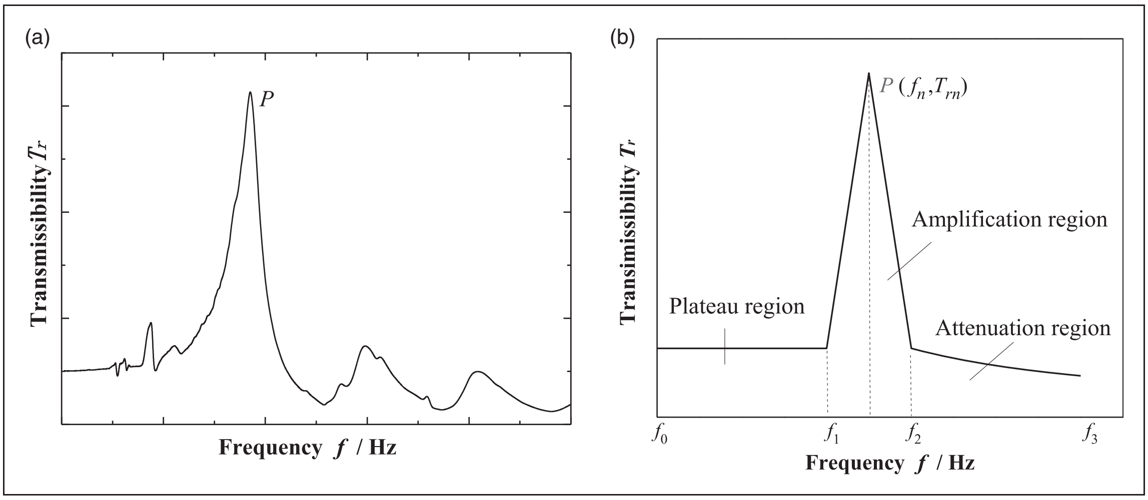

Figure 3. Simplification of vibration transmissibility curve for paper honeycomb sandwich plate. (a) Typical vibration transmissibility curve and (b) simplified diagram.

Table 2. The experimental results and the damping energy dissipation.

Number	f_n (Hz)	T_{rn}	W_1 (J)	W_{23} (J)	W_4 ($\times 10^{-3}$ J)	W_{all} (J)
S6/20-M12.85	348.9	2.830	64.67	0.0308	3.02	64.71
S6/20-M16	341.1	3.023	73.08	0.0414	3.74	73.12
S6/20-M20.85	314.6	3.456	75.72	0.0683	5.11	75.80
S6/20-M24	311.0	3.609	82.22	0.0825	5.75	82.30
S8/20-M12.85	329.8	3.411	49.65	0.0379	2.87	49.69
S8/20-M16	315.3	4.236	46.82	0.0591	3.14	46.88
S8/20-M20.85	283.0	4.364	53.05	0.0982	4.81	53.15
S8/20-M24	270.4	5.041	50.16	0.1373	5.08	50.30
S10/20-M12.85	306.2	4.340	35.59	0.0513	2.60	35.64
S10/20-M16	287.5	4.981	36.01	0.0800	3.13	36.09
S10/20-M20.85	261.6	5.461	38.80	0.1355	4.24	38.94
S10/20-M24	219.0	5.884	34.60	0.2387	5.48	34.85
S10/30-M12.85	266.3	5.741	23.12	0.0835	2.43	23.21
S10/30-M16	252.3	6.035	25.91	0.1209	3.07	26.03
S10/30-M20.85	225.1	6.363	28.52	0.2080	4.28	28.73
S10/30-M24	202.1	6.896	27.14	0.3199	5.00	27.46
S10/40-M12.85	239.3	7.006	16.94	0.1219	2.25	17.06
S10/40-M16	194.4	7.283	16.45	0.2421	3.25	16.70
S10/40-M20.85	179.2	7.503	19.18	0.3839	4.37	19.56
S10/40-M24	167.9	7.957	19.47	0.5333	4.95	20.01

frequency f_n and ordinate is maximum vibration transmissibility ratio T_{rn}. The experimental results of resonance frequency and maximum vibration transmissibility ratio are shown in Table 2.

According to the characteristics of vibration transmissibility curve at different regions, the simplified vibration transmissibility ratio–frequency curves could be expressed by piecewise functions. In the plateau region, $f_0 < f < f_1$, the vibration transmissibility ratio in this region (T_{r1}) can be expressed as

$$f_0 < f < f_1, T_{r1} \approx 1 \tag{1}$$

In the left half part of the amplification region, $f_1 < f < f_n$, the vibration transmissibility ratio in this region (T_{r2}) can be expressed as

$$f_1 < f < f_n, \text{ Given } T_{r2} \approx k_1 f + b_1 \tag{2}$$

In the right half part of the amplification region, $f_n < f < f_2$, the vibration transmissibility ratio in this region (T_{r3}) can be expressed as

$$f_n < f < f_2, \text{ Given } T_{r3} \approx k_2 f + b_2 \tag{3}$$

In the attenuation region, $f_2 < f < f_3$, the vibration transmissibility ratio in this region (T_{r4}) can be expressed as

$$f_2 < f < f_3,\ T_{r4} \approx \frac{f_2}{f} \tag{4}$$

The experimental results of vibration transmissibility of paper honeycomb sandwich plate show that the frequency range of amplification region is almost ±50 Hz of resonance frequency and amplification region is symmetrical with the axis of resonance frequency. That is, $f_1 = f_n - 50$, $f_2 = f_n + 50$.[13] The slope of curve in left and right parts of the amplification region can be expressed as

$$k_1 = \frac{T_{rn} - 1}{50}, \quad k_2 = -\frac{T_{rn} - 1}{50} \tag{5}$$

As the vibration transmissibility curve passes through the point (f_n, T_{rn}), the intercept of vibration transmissibility curves of two parts in amplification region can be calculated

$$b_1 = \left(1 - \frac{f_n}{50}\right)T_{rn} + \frac{f_n}{50}, \quad b_2 = \left(1 + \frac{f_n}{50}\right)T_{rn} - \frac{f_n}{50} \tag{6}$$

In summary, the vibration transmissibility curve of paper honeycomb sandwich plate can be expressed as a function of frequency. That is

$$T_r = \begin{cases} 1, & f_0 < f \leqslant f_1 \\ \dfrac{T_{rn}-1}{50}f + \left[\left(1 - \dfrac{f_n}{50}\right)T_{rn} + \dfrac{f_n}{50}\right], & f_1 < f \leqslant f_n \\ -\dfrac{T_{rn}-1}{50}f + \left[\left(1 + \dfrac{f_n}{50}\right)T_{rn} - \dfrac{f_n}{50}\right], & f_n < f \leqslant f_2 \\ \dfrac{f_2}{f}, & f_2 < f \leqslant f_3 \end{cases} \tag{7}$$

Calculation of damping energy dissipation for paper honeycomb sandwich plate-block system

Basic theory of damping energy dissipation

According to the basic principle of vibration mechanics, the damping energy dissipation of system in a period (W_c) is the mechanical energy consumed by damping force.[14] The work done by damping force in a period is integrated, and W_c is obtained as follows

$$W_c = \oint c\dot{x}(t)\mathrm{d}x = \int_0^T c\dot{x}(t)^2 \mathrm{d}t \tag{8}$$

According to the basic theory of transportation packaging,[15] the steady-state response acceleration of a single-degree-of-freedom linear system under harmonic excitation acceleration $\ddot{y}(t) = A\sin\omega t$ is $\ddot{x}(t) = T_r A\sin(\omega t - \beta)$, the expression of velocity $\dot{x}(t)$ is obtained by one time integral of response acceleration

$$\dot{x}(t) = -\frac{T_r A}{\omega}\cos(\omega t - \beta) \tag{9}$$

Substituting equation 9 into equation 8 and calculating the integral, the dissipated energy at any frequency when a single-degree-of-freedom linear system is excited under harmonic excitation acceleration is as follows

$$W_c = \frac{cA^2T_r^2}{\omega^2}\int_0^{\frac{2\pi}{\omega}} \cos^2(\omega t - \varphi)\mathrm{d}t = \frac{\pi cA^2T_r^2}{\omega^3} = \frac{cA^2T_r^2}{8\pi^2 f^3} \tag{10}$$

where c represents the damping property of the cushioning material, namely

$$c = 2m\xi\omega_n = 4\pi m\xi f_n \tag{11}$$

Yet, ξ is the damping ratio, which can be estimated as follows

$$\xi \approx \frac{1}{\sqrt{T_{rn}^2 - 1}} \tag{12}$$

Calculation of damping energy dissipation

Equation 10 expresses the energy dissipated by the damping force at any frequency of a single-degree-of-freedom linear system in a period. In the equation, T_r and f represent the vibration transmissibility ratio and frequency at any point on the vibration transmissibility curve of the packaging material. Substituting equation 7 into equation 10, the dissipated energy of damping force at any frequency of the paper honeycomb sandwich plate-block system in a period can be obtained, which is a one-variable function of frequency

$$W_c = \begin{cases} \dfrac{cA^2}{8\pi^2 f^3}, & f_0 < f \leqslant f_1 \\ \dfrac{cA^2}{8\pi^2}\left\{\dfrac{T_{rn}-1}{50}\dfrac{1}{\sqrt{f}} + \left[\left(1 - \frac{f_n}{50}\right)T_{rn} + \frac{f_n}{50}\right]\frac{1}{\sqrt{f^3}}\right\}^2, & f_1 < f \leqslant f_n \\ \dfrac{cA^2}{8\pi^2}\left\{-\dfrac{T_{rn}-1}{50}\dfrac{1}{\sqrt{f}} + \left[\left(1 + \frac{f_n}{50}\right)T_{rn} - \frac{f_n}{50}\right]\frac{1}{\sqrt{f^3}}\right\}^2, & f_n < f \leqslant f_2 \\ \dfrac{cA^2 f_2^2}{8\pi^2 f^5}, & f_2 < f \leqslant f_3 \end{cases} \tag{13}$$

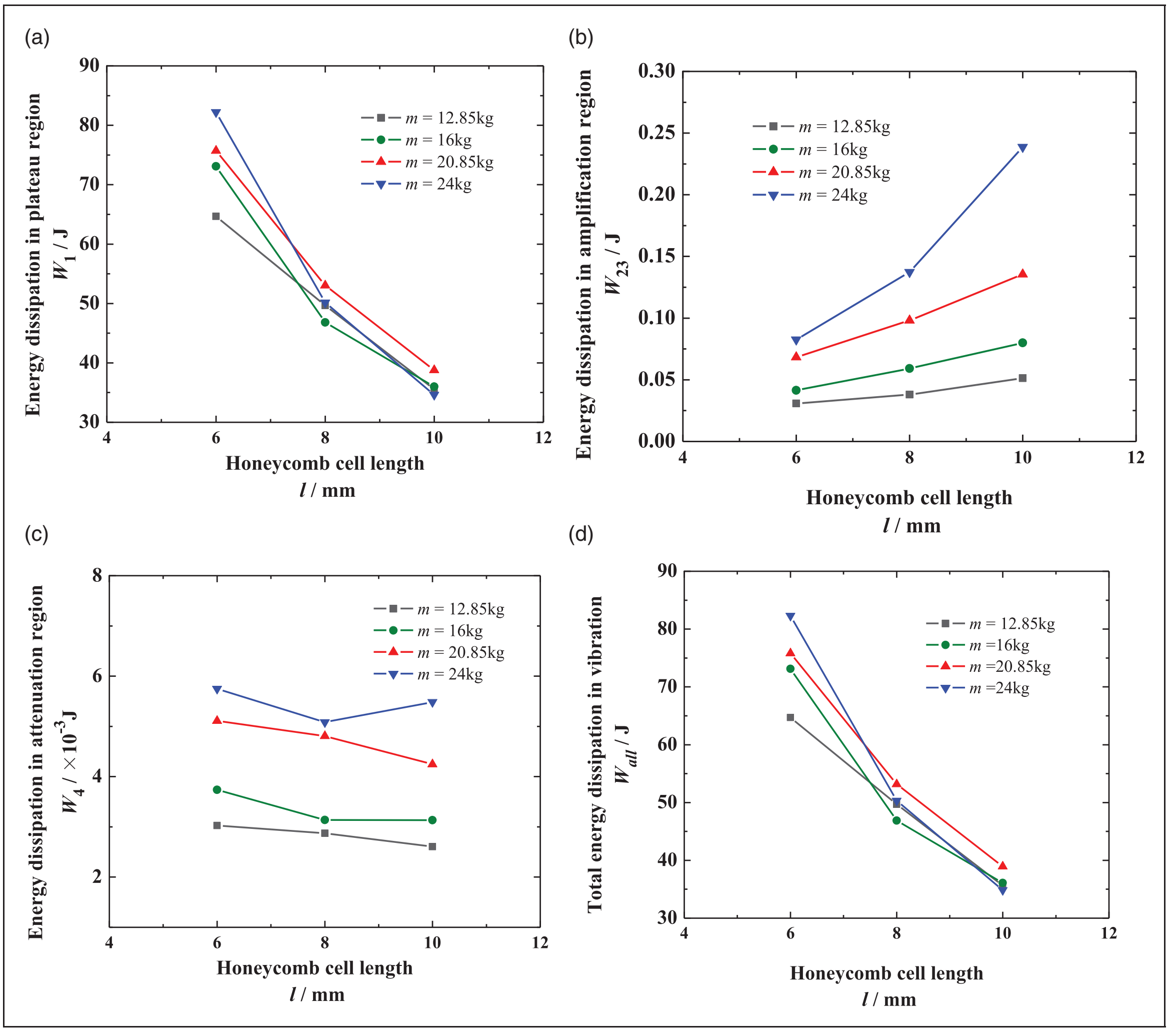

Figure 4. Influence of honeycomb cell length on damping energy dissipation of paper honeycomb sandwich plate-block system under different masses of block: (a) Influence of honeycomb cell length l on energy dissipation in plateau region W_1, (b) Influence of honeycomb cell length l on energy dissipation in amplification region W_{23}, (c) Influence of honeycomb cell length l on energy dissipation in attenuation region W_4, and (d) Influence of honeycomb cell length l on total energy dissipation in all regions W_{all}.

The total energy of each region could be obtained by integration of the equation 13 in each region. The damping energy dissipation in plateau region (W_1) is

$$W_1 = \frac{cA^2}{8\pi^2}\int_{f_0}^{f_1}\frac{1}{f^3}\mathrm{d}f = \frac{cA^2}{16\pi^2}(f_0^{-2} - f_1^{-2}) \tag{14}$$

The damping energy dissipation in the left half part of amplification region (W_2) is

$$\begin{aligned} W_2 &= \frac{cA^2}{8\pi^2}\int_{f_1}^{f_n}\left\{\frac{T_{rn}-1}{50}\frac{1}{\sqrt{f}} + \left[\left(1-\frac{f_n}{50}\right)T_{rn} + \frac{f_n}{50}\right]\frac{1}{\sqrt{f^3}}\right\}^2\mathrm{d}f \\ &= \frac{cA^2}{8\pi^2}\left[k_1^2\ln\frac{f_n}{f_1} + 2k_1b_1(f_1^{-1} - f_n^{-1}) + \frac{b_1^2}{2}(f_1^{-2} - f_n^{-2})\right] \end{aligned} \tag{15}$$

The damping energy dissipation in the right half part of amplification region (W_3) is

$$\begin{aligned} W_3 &= \frac{cA^2}{8\pi^2}\int_{f_n}^{f_2}\left\{-\frac{T_{rn}-1}{50}\frac{1}{\sqrt{f}} + \left[\left(1+\frac{f_n}{50}\right)T_{rn} - \frac{f_n}{50}\right]\frac{1}{\sqrt{f^3}}\right\}^2\mathrm{d}f \\ &= \frac{cA^2}{8\pi^2}\left[k_2^2\ln\frac{f_2}{f_n} + 2k_2b_2(f_n^{-1} - f_2^{-1}) + \frac{b_2^2}{2}(f_n^{-2} - f_2^{-2})\right] \end{aligned} \tag{16}$$

The damping energy dissipation in the attenuation region (W_4) is

$$W_4 = \frac{cA^2 f_2^2}{8\pi^2}\int_{f_2}^{f_3}\frac{1}{f^5}\mathrm{d}f = \frac{cA^2}{32\pi^2}(f_2^{-2} - f_2^2 f_3^{-4}) \tag{17}$$

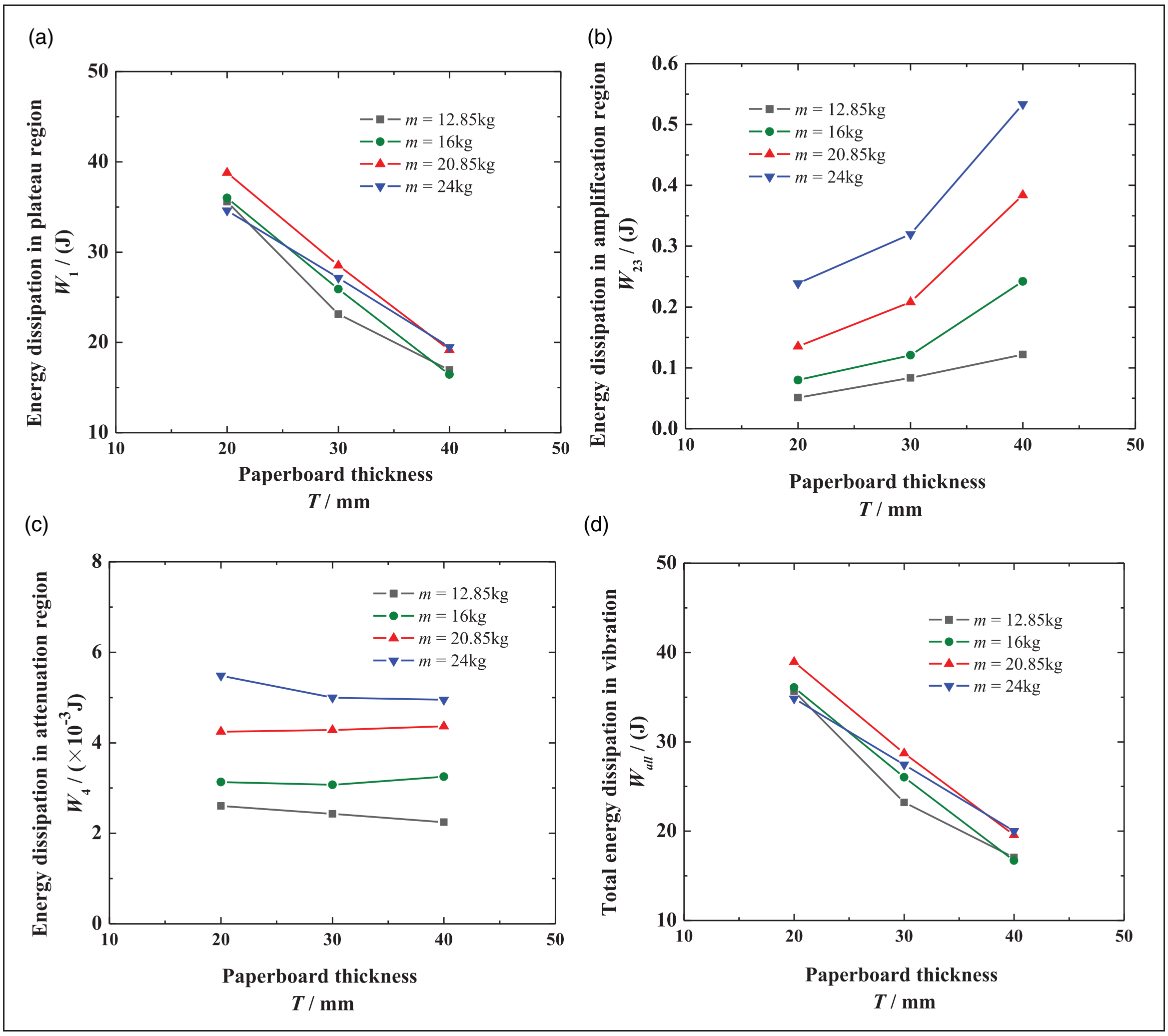

Figure 5. Influence of paperboard thickness on damping energy dissipation of paper honeycomb sandwich plate-block system under different masses of block: (a) Influence of paperboard thickness T on energy dissipation in plateau region W_1, (b) Influence of paperboard thickness T on energy dissipation in amplification region W_{23}, (c) Influence of paperboard thickness T on energy dissipation in attenuation region W_4, and (d) Influence of paperboard thickness T on total energy dissipation in all regions W_{all}.

In summary, the damping energy dissipation in amplification region (W_{23}) is

$$W_{23} = W_2 + W_3 \tag{18}$$

The total damping energy dissipation of paper honeycomb sandwich plate-block system in all regions (W_{all}) is

$$W_{all} = W_1 + W_2 + W_3 + W_4 \tag{19}$$

Substituting the experimental data in Table 2 into equations 14 to 19, in which f_0 is 5 Hz, f_3 is 500 Hz, and the letter A (indicates amplitude of excitation acceleration) is 4.9 m/s^2 in this experiment, the energy dissipation of paper honeycomb sandwich plate-block system in each region and total energy dissipation in all regions under each experimental condition were obtained, as shown in Table 2. It is clear that the energy dissipation of system in the plateau region is the largest, followed by the amplification region, and the attenuation region is the smallest. In more detail, the energy dissipation of the amplification region is almost 10^{-2} times that of the plateau region, and the energy dissipation of the attenuation region is almost 10^{-4} times that of the plateau region. The total energy dissipation in all regions is almost equal to the energy dissipation in the plateau region.

Influence analysis of damping energy dissipation for paper honeycomb sandwich plate-block system

Figure 4 illustrates the effect of honeycomb cell length on damping energy dissipation of paper honeycomb sandwich plate-block system. It can be seen that the influence of honeycomb cell length on energy dissipation of the plateau region is almost the same as on total energy dissipation in all regions, that is, with the increase of cell length, energy dissipation decreases.

The energy dissipation in the amplification region increases with the increase of cell length and with the increase of block mass, the influence of cell length on energy dissipation in the amplification region is greater. But the energy dissipation in the attenuation region does not change obviously with the cell length.

Figure 5 illustrates the effect of sandwich plate thickness on damping energy dissipation of paper honeycomb sandwich plate-block system. It can be seen that the thickness of paper honeycomb sandwich plate has almost the same effect on the energy dissipation of the plateau region and on total energy dissipation in all regions, that is, the energy dissipation decreases with the increase of the plate thickness. The energy dissipation in the amplification region increases with the increase of the thickness of sandwich plate. In addition, the influence of sandwich plate thickness on energy dissipation in the amplification region is greater with the increase of block mass. Yet, the energy dissipation in the attenuation region does not change obviously with the plate thickness.

Summarizing Figures 4 and 5, it can be concluded that different honeycomb structural parameters (cell length and sandwich plate thickness) have the same effect on the damping energy dissipation of paper honeycomb sandwich plate-block system. The mass of block has little effect on energy dissipation of the plateau region and total energy dissipation, but it has great influence on that of amplification and attenuation region. As the mass increases, the energy dissipation in amplification and attenuation region increases. The total energy dissipation of system in all regions is about equal to that of plateau region, and the energy dissipation in amplification and attenuation region can be neglected.

Conclusions

The vibration transmissibility of paper honeycomb sandwich plate was tested and the vibration transmissibility curve was simplified and characterized; furthermore, the calculation of energy dissipation for paper honeycomb sandwich plate-block system was derived based on the basic principles of vibration mechanics, and the influence rules of honeycomb structural parameters (honeycomb cell length and sandwich plate thickness) and block mass on the damping energy dissipation of the system were analyzed. The conclusions are as follows:

1. The vibration transmissibility ratio–frequency curve of paper honeycomb sandwich plate can be divided into three regions: plateau region, amplification region, and attenuation region. The vibration transmissibility ratio in different regions can be expressed as functions of frequency.
2. The damping energy dissipation of paper honeycomb sandwich plate depends on its vibration transmissibility, especially the resonance frequency and maximum vibration transmissibility ratio. If the vibration transmissibility ratio–frequency curve is obtained, the energy dissipation can be calculated. This method may apply for other packaging material to calculate the damping energy dissipation of packaging system.
3. The energy dissipation of the amplification region is almost 10^{-2} times that of the plateau region, and the energy dissipation of the attenuation region is almost 10^{-4} times that of the plateau region. The total energy dissipation of paper honeycomb sandwich plate-block system during all the vibration progress is approximately equal to that in the plateau region, and the energy dissipation in the amplification and attenuation region can be neglected.
4. The influence rule of different honeycomb structural parameters (honeycomb cell length or sandwich plate thickness) on the damping energy dissipation of paper honeycomb sandwich plate-block system is the same, that is, with the increase of structural parameters, the energy dissipation in the plateau region and the total energy dissipation in all the regions decreases; the energy dissipation in the amplification region increases with the increase of structural parameters; and the energy dissipation in the attenuation region does not change significantly with structural parameters. The block mass has little effect on the energy dissipation in the plateau region and on the total energy dissipation but has a greater impact on the energy dissipation in the amplification and attenuation regions.

Declaration of Conflicting Interests

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