

Comparison Studies on Dynamic Packaging Properties of Corrugated Paperboard Pads

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Abstract

Corrugated paperboard is a kind of inexpensive and environmental-friendly packaging material, and may be made into pads of package cushioning to protect products from shock and vibration damage by isolation during distribution. This article deals with the characterization of dynamic packaging properties of corrugated paperboard pads, such as dynamic cushioning curves, vibration transmissibility and frequency curves. The main feature of article is the evaluation on the dynamic shock cushioning property and vibration transmissibility of corrugated paperboard pads by a series of experimental studies on the drop shock tester and vibration tester, the establishment of experimental formulas of dynamic cushioning curves, and the analysis of resonance frequencies and vibration transmissibility. By using the fitting polynomial of curve and method of the least mean square, the experimental formulas with third order polynomial function of dynamic cushioning curves for corrugated paperboard pads are obtained. By using linear vibration theory with single degree of freedom, the resonance frequencies, vibration transmissibility and damping ratios of corrugated paperboard pads at different static loads are acquired. All results show the dynamic properties relevant to design applications of corrugated paperboard pads for protective packaging.

Keywords: Corrugated Paperboard Pads, Dynamic Shock Cushioning Property, Dynamic Cushioning Curve, Vibration Transmissibility, Resonance Frequency

1. Introduction

Corrugated paperboard is a kind of inexpensive and environmental-friendly packaging material with corrugated sandwich structure, holds lightweight, high strength-to-weight and stiffness-to-weight ratios, and has economic and environmental advantages over plastic foams [1,2]. It also has excellent machining technology of packaging, and may be made into pads of package cushioning to protect products from shock and vibration damage by isolation during distribution. The usual technology is to interpose the corrugated paperboard pad between the product and the container to provide the necessary isolation [3-5]. So, there is an increasing interest in utilizing corrugated paperboard pads for protective packaging of products (e.g. precise equipment and instrument, household appliance and fragile goods etc).

For corrugated paperboard, the compressive strength, crush strength, bending deflection and flexural stiffness, creep property and recoverability were investigated by

Hahn, Lee, Urbanik, Guo *et al.* [6-9]. By using some finite element models and commercial finite element code ABAQUS or ANSYS, the mechanical behaviors of corrugated paperboard such as buckling, transverse shear, elasticity, stability, collapse and ultimate failure were studied by Gilchrist, Nordstrand, Aboura, Rami, Talbi *et al.* [10-14]. Within the finite element models (e.g. thin shell element, simplified homogenization model), both geometric nonlinearity (large deformation) and material nonlinearity (anisotropy or orthotropy) effects were considered. The cushioning property and its predictive model, the vibration transmissibility and frequency response of single-wall corrugated paperboard were analyzed by Sek *et al.* [15,16]. But for the corrugated paperboard pads (e.g. single layer pad, two layers pad, three layers pad), the lack of dynamic packaging properties such as dynamic cushioning curves and vibration transmissibility hampers its application for protective packaging of products [4-5]. Therefore the aims of this research work are as follows: Firstly, evaluate the dy-

dynamic shock cushioning property of corrugated paperboard pads by drop shock tests, and establish the experimental formulas of dynamic cushioning curves. Secondly, study the vibration transmissibility of corrugated paperboard pads at different static loads by vibration tests, and analyze the resonance frequencies, vibration transmissibility and damping ratios.

2. Structure of Corrugated Paperboard Pads

The structure of corrugated paperboard pads usually covers single layer corrugated paperboard pad in **Figure 1(a)**, two layers corrugated paperboard pad in **Figure 1(b)**, and three layers corrugated paperboard pad in **Figure 1(c)**. The difference of these pads is the layer quantity (or thickness of pad). The thicknesses of single layer pad, two layers pad, three layers pad are 7.81 mm, 15.62 mm and 23.43 mm, respectively. The top surface of all test specimens is square, and the dimension is 15 cm × 15 cm. They would be respectively called single layer pad, two layers pad, three layers pad for short.

These corrugated paperboard pads are also made of double-wall corrugated paperboard with A and B flutes by machining technology of cutting, folding and pasting. The single layer pad is directly made of the double-wall corrugated paperboard, the structure of two layers pad comprises two layers of the double-wall corrugated paperboard, and the structure of three layers pad consists of three layers of the double-wall corrugated paperboard. The thickness of double-wall corrugated paperboard with A and B flutes is 7.81 mm, the corrugated cores and inner sheet are corrugated paper with grammage of 150 g/m², and the face sheets are kraft linerboard with grammage of 250 g/m². Before each of tests, all test

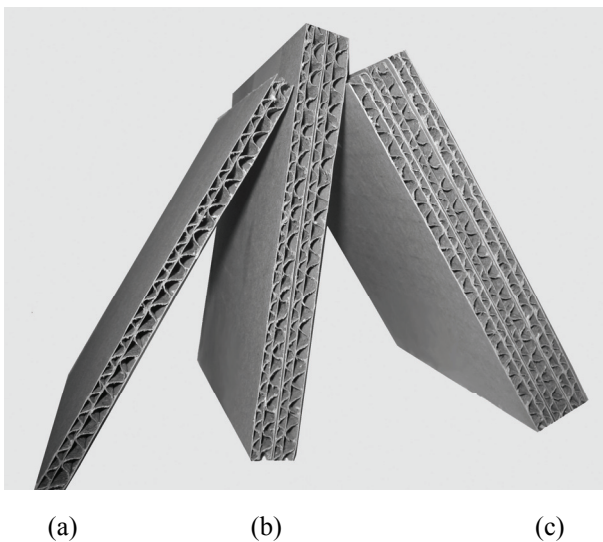


Figure 1. Photograph of corrugated paperboard pads.

specimens of corrugated paperboard pads should be pre-conditioned to equilibrium in air uniformly maintained for at least 24 hours at ambient temperature 23°C and relative humidity 60%.

3. Description of Dynamic Packaging Properties

3.1. Description of Dynamic Shock Cushioning Property

The dynamic shock cushioning property describes the capability of absorbing drop shock energy of corrugated paperboard pads, and reflects the relationship between peak acceleration and static stress during drop shock. The peak acceleration is a non-dimension ratio of peak acceleration of the packaged item to gravity acceleration. It is usually presented as a family of dynamic cushioning curves (or peak acceleration and static stress curve), which shows peak acceleration during drop shock for a range of static loads and is constructed for several drop heights [3]. The test system for dynamic shock cushioning property (**Figure 2**) shall consist of a drop shock tester, a signal acquisition & processing device, a set of Data Acquisition & Signal Processing Engineering Technology (DASP-ET) software. The drop shock tester has a drop block and weight (to represent the packaged item) and impact base for dynamic loading of a test specimen to simulate drop shock in handling. The weight is mounted on the drop block. The mass of weight and drop height of the drop block are adjustable. An acceleration sensor is mounted on the drop block, and the signal output from the acceleration sensor is firstly fed into the signal acquisition & processing device, then the drop shock acceleration and time curve may be read and displayed by DASP-ET.

While the drop block with the weight impacts the test specimen of corrugated paperboard pad from a predetermined drop height by means of area contact, according to the law of conservation of energy, the potential energy of weight and drop block shall be transferred as the kinetic energy of weight and drop block and the deformation energy of test specimen [3]. The relationship may be described as the following expression

$$\frac{1}{2}mV^2 + AT \int_0^\varepsilon \sigma(\varepsilon) d\varepsilon = mg(h + T\varepsilon) \quad (1)$$

where m stands for mass of drop block and weight, V is impact velocity of weight and drop block, A is contact area between test specimen and drop block, T is thickness of test specimen, σ and ε are compression stress and strain of test specimen, and h is a predetermined drop height. When the impact velocity of weight and drop block becomes zero ($V = 0$), the maximum deformation

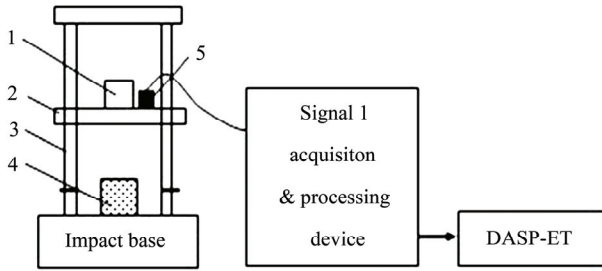


Figure 2. Test system of dynamic shock cushioning property: 1.Weight; 2.Drop block; 3.Guide column; 4.Test specimen 5. Acceleration sensor.

ϵ_m of test specimen is reached, and the maximum stress σ_m of test specimen and peak acceleration G_m would be occurred, and Equation (1) may be rewritten as

$$\int_0^{\epsilon_m} \sigma(\epsilon) d\epsilon = \frac{mg}{A} \left(\frac{h}{T} + \epsilon_m \right) = \sigma_s \left(\frac{h}{T} + \epsilon_m \right) \quad (2)$$

where σ_s is static stress exerted on test specimen. In addition, according to the Newton’s law of motion, the maximum force exerted on weight and drop block equals to its inertial force plus its own weight [3], and the relationship may be written as

$$\sigma_m = (G_m + 1)\sigma_s \quad (3)$$

where G_m is peak acceleration divided by gravity acceleration g . Then substituting Equation (3) into Equation (2), the following expression may be derived

$$G_m = \frac{\sigma_m}{\int_0^{\epsilon_m} \sigma(\epsilon) d\epsilon} \left(\frac{h}{T} + \epsilon_m \right) - 1 \quad (4)$$

where $\frac{\sigma_m}{\int_0^{\epsilon_m} \sigma(\epsilon) d\epsilon}$ is the ratio of maximum stress to unit

volume stored energy. It is obvious that peak acceleration may directly indicate the capability of absorbing drop shock energy of corrugated paperboard pad, and may express the dynamic shock cushioning property of corrugated paperboard pad. So the dynamic cushioning curve has proved to be the most practical basis for describing the dynamic shock cushioning property, the lower the dynamic cushioning curve swings, and the better protection the package cushioning provides [4,5].

3.2. Description of Vibration Transmissibility

The vibration transmissibility is usually described as the relationship between vibration transmissibility and resonance frequency of corrugated paperboard pads at different static loads. Vibration transmissibility is a non-dimension ratio of response acceleration amplitude of the packaged item in steady-state forced vibration to excitation acceleration amplitude [3]. The test system for vibration

transmissibility (**Figure 3**) shall consist of a dynamo-electric vibration tester, a signal acquisition & processing device, a set of DASP-ET software. Two test specimens combination under investigation are placed in the test fixture, and the mass block is placed on the bottom test specimen. The two test specimens, mass block (to represent the packaged item) and fixture are mounted on the vibration tester. The weight of mass block is changeable, and the static load exerted on the bottom test specimen may be adjusted by changing the weight of mass block. One acceleration sensor is attached to the platform of vibration table to monitor the excitation acceleration, and the other is located in the mass block to measure the response acceleration. The signal outputs from the sensor located in the mass block and on the platform of vibration table are simultaneously fed into the signal acquisition & processing device, then the experimental data shall be analyzed and presented in the form of vibration transmissibility and frequency curve by DASP-ET.

Although most package cushioning materials exhibit nonlinear property, a brief discussion of linear system with single degree of freedom will aid in understanding some of the fundamental aspects of vibration as related to packaging considerations [4,5]. For the vibration test system in **Figure 3**, the mass block cushioned on the test specimen may be idealized as the linear single degree of freedom system with viscous damping, and the vibration transmissibility T_r of package cushioning system with corrugated paperboard pads would be described as

$$T_r = \sqrt{\frac{1 + (2\xi\lambda)^2}{(1 - \lambda^2)^2 + (2\xi\lambda)^2}} \quad (5)$$

where λ stands for frequency ratio ($\lambda = \frac{f}{f_r}$), f is excitation frequency of vibration table, f_r is resonance frequency of the package cushioning system, and ζ represents damping ratio. It is evident that vibration transmissibility has a close relationship with frequency ratio and damping ratio. When the resonance takes place ($\lambda = 1$), the damping ratio ζ may be derived from Equation (5) and written as

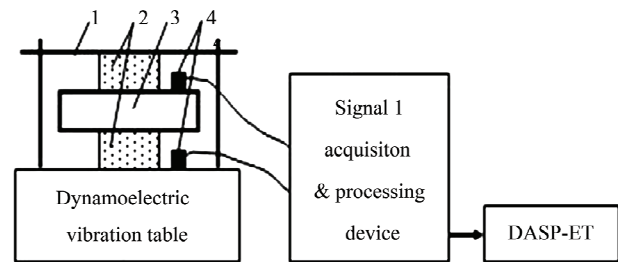


Figure 3. Test system of vibration transmissibility: 1) Clamp device; 2) Test specimens; 3) Mass block; 4) Acceleration sensors.

$$\xi = \frac{1}{2} \sqrt{\frac{1}{T_r^2} - 1} \quad (6)$$

So, after obtaining the vibration transmissibility and frequency curves of corrugated paperboard pads by vibration tests with slow sine sweep, resonance frequencies, vibration transmissibility and damping ratios may be analyzed, and the vibration transmissibility of corrugated paperboard pads shall be comprehensively evaluated.

4. Experimental Methods of Dynamic Packaging properties

The most comprehensive method for determining dynamic shock cushioning property is described in the standard ASTM D 1596 "Standard test method for dynamic shock cushioning characteristics of packaging materials". The test procedure is as follows: Firstly, position the test specimen on the impact base and prepare the drop block to impact the test specimen. Secondly, impact the test specimen at the predetermined drop block weight (static load) and drop height, then repeat the same test procedure with the other two test specimens. The drop shock acceleration and time curve should be recorded for each test. The average value of peak accelerations for these three drop shock tests is taken as the peak acceleration at the predetermined static load. Thirdly, repeat the drop shock procedure with several more increments of weight until sufficient data are derived to establish the dynamic cushioning curve. Lastly, the same procedure shall be employed for different drop heights. For a drop height, a piece of dynamic cushioning curve may be obtained by making drop shock tests for a range of static loads. Then adjusting the drop height and making similar drop shock tests, another piece of dynamic cushioning curve may be also obtained. Therefore by making a series of drop shock tests for different drop heights, a family of dynamic cushioning curves should be obtained. On the basis of the family of dynamic cushioning curves, the dynamic shock cushioning property of corrugated paperboard pads shall be thoroughly evaluated.

The most comprehensive method for determining vibration transmissibility is described in the standard ASTM D 4168 "Standard test method for vibration transmissibility of package cushioning material". The test procedure is as follows: Firstly, place two specimens combination under investigation in the test fixture, one below and the other above the mass block. The mass block weighted for the desired static load is placed on the bottom test specimen, and the top test specimen is placed above the mass block, then the fixture is clamped in place. Secondly, start the vibration test with slow sine sweep, and present experimental data in the form of vibration transmissibility and frequency curve. In order to thoroughly evaluate the vibration transmissibility of cor-

rugated paperboard pads, the range of frequency sweep is selected from 3 Hz to 600 Hz in order to wholly investigate on the vibration property of corrugated paperboard pads. The frequency sweep rate is one octave per minute, and sine excitation acceleration is held constant amplitude at 0.5 g. Thirdly, the same procedure shall be used for different static loads. These different static loads would be selected from the family of dynamic cushioning curves of corrugated paperboard pads. On the basis of vibration transmissibility and frequency curves at different static loads, the vibration transmissibility of corrugated paperboard pads would be investigated.

5. Results and Discussions

5.1. Dynamic Shock Cushioning Property of Corrugated Paperboard Pads

According to the test method ASTM D 1596, the drop shock tests of corrugated paperboard pads are made for drop heights 30 cm, 60 cm and 90 cm respectively. The waves of drop shock acceleration are similar to half-sine pulses at different static loads for different drop height, e.g. the wave in **Figure 4** is that of single layer pad for drop height (DH) 30 cm and static load 2.439 kPa, the peak acceleration is 177.46 g (gravity acceleration). In addition **Figure 5** provides the wave of two layers pad for drop height 60 cm and static load 2.613 kPa, the peak acceleration is 203.61 g. **Figure 6** is the wave of three layers pad while drop height 90 cm and static load 3.049 kPa, the peak acceleration is 291.14 g. Due to the limited space other drop shock acceleration and time curves are omitted.

By comparison studies on the drop shock tests for corrugated paperboard pads, seven pieces of dynamic cushioning curve shall be obtained, which are shown in **Figures 7 to 9**. For single layer pad, while the drop height is 60 cm or 90 cm, the test specimens would be wholly crushed and lose dynamic shock cushioning property, so it has only one piece of dynamic cushioning curve for drop height 30 cm (**Figure 7**). The curves in **Figure 8** are for two layers pad, and that of **Figure 9** are for three layers pad.

These dynamic cushioning curves are the most practical basis for the package cushioning design procedure of corrugated paperboard pads [4-5], so it is necessary to develop experimental formulas of these curves. From the characterization of dynamic cushioning curves summarized above, these curves have a close relationship with the drop height and static stress. When the drop height is constant, the peak acceleration may be described as a function of static stress, and the experimental formulas of dynamic cushioning curves may be established by using the fitting polynomial of curve [17-18]. By comparing

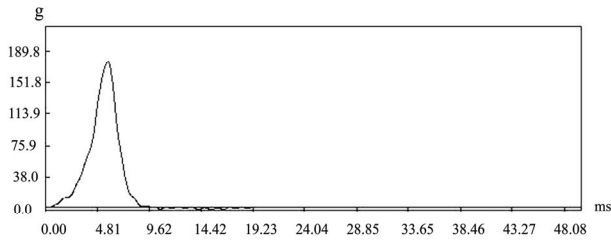


Figure 4. Drop shock acceleration and time curve of single layer pad.

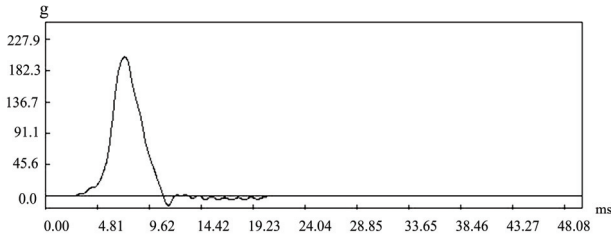


Figure 5. Drop shock acceleration and time curve of two layers pad.

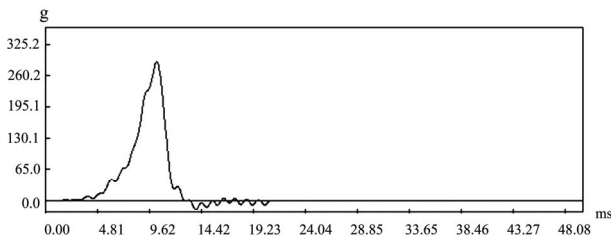


Figure 6. Drop shock acceleration and time curve of three layers pad.

the test data of average peak acceleration with its theoretical data derived from the fitting polynomial of curve, the third order polynomial function of static stress has proved to be the best expression, and the experimental formulas of dynamic cushioning curves of corrugated paperboard pads is written as

$$G_m = a_0 + a_1\sigma_s + a_2\sigma_s^2 + a_3\sigma_s^3 \quad (7)$$

where G_m is average peak acceleration, σ_s represents static stress, a_0, a_1, a_2, a_3 are four characteristic factors. For example, **Figure 10** gives the dynamic cushioning curve of three layers pad at drop height 60 cm, and the circle dots stand for test data of average peak acceleration. The dynamic cushioning curve is obtained by using the fitting polynomial with third order polynomial function of the curve. So, on the basis of test data of average peak acceleration and static stress obtained from the drop shock tests of corrugated paperboard pads for drop heights 30 cm, 60 cm and 90 cm respectively, using Equation (7) and Method of the Least Mean Square, the characteristic factors of dynamic cushioning curves are solved and shown in **Table 1**.

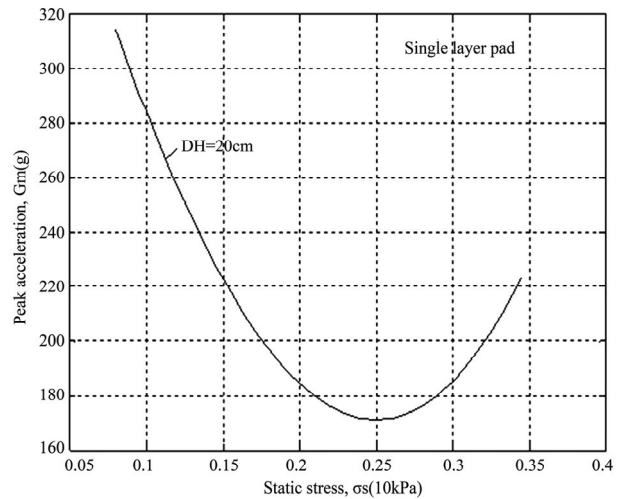


Figure 7. Dynamic cushioning curve of single layer pad.

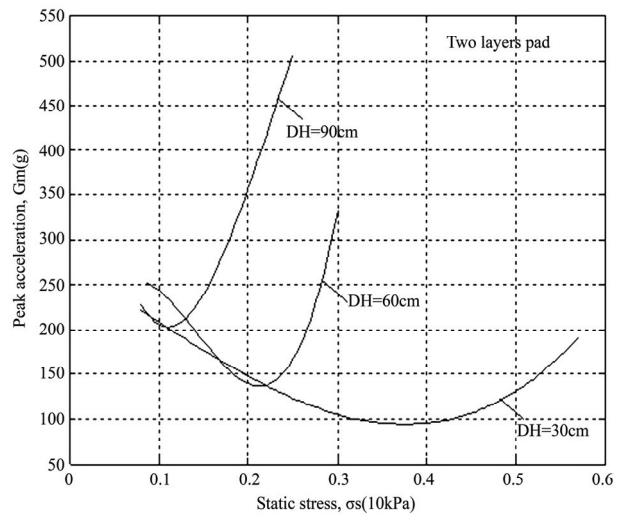


Figure 8. Dynamic cushioning curves of two layers pad.

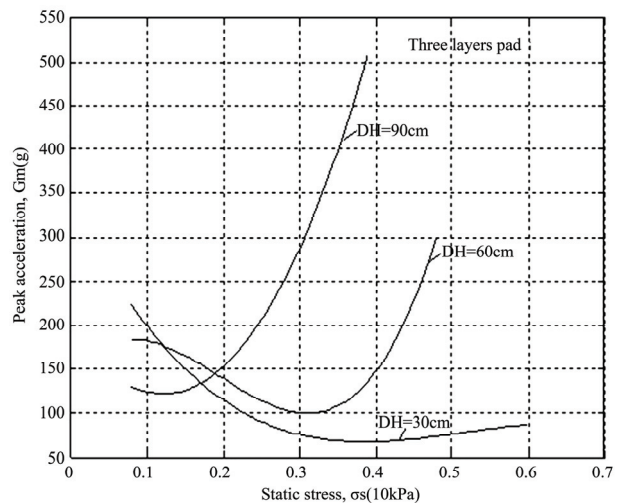


Figure 9. Dynamic cushioning curves of three layers pad.

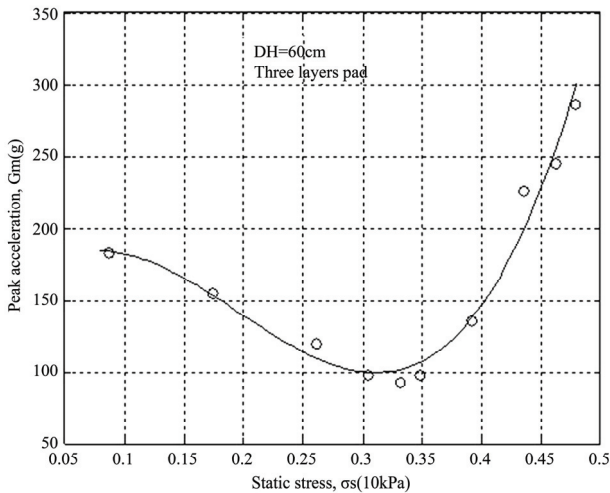


Figure 10. Dynamic cushioning curves of three layers pad (DH = 60 cm).

By comparing and analyzing these dynamic cushioning curves of corrugated paperboard pads, some conclusions may be drawn as follows:

1) Each piece of dynamic cushioning curves of corrugated paperboard pads (**Figures 7-9**) is always concave and upward, and has only one minimum value point. This rule can be understood as follows [5]. If the mass of weight and drop block is light, the drop shock would result in very little compressive deformation, and the corrugated paperboard pad absorbs and stores a little mechanical energy per unit volume, so the acceleration peak is relatively large. This represents the left hand side of dynamic cushioning curve. In the middle area, the corrugated paperboard pad is properly compressed and absorbs and stores much mechanical energy per unit volume, so the minimum peak acceleration shall be reached. After passing through a certain point, the greater mass of weight and drop block compresses the corrugated paperboard pad too much, so the corrugated paperboard pad shall be bottomed out, then the minimum peak accel-

eration increases. This is the right hand side of the curve. So the middle area of the curve is the optimum performance range.

2) For the same corrugated paperboard pad, with the increment of drop height, the concave point of dynamic cushioning curves (**Figures 8 and 9**) has a trend to rise along leftward and upward direction. Therefore the drop height is an important factor to influence on the dynamic shock cushioning property, and the selection of dynamic cushioning curve should be coincided with the predetermined drop height in package cushioning design of corrugated paperboard pads.

3) For the same drop height, with the increment of layer quantity of corrugated paperboard pads, the minimum peak acceleration declines. The minimum peak acceleration of three layers pad is least. So three layers pad holds better dynamic shock cushioning property than single layer pad and two layers pad.

5.2. Vibration Transmissibility of Corrugated Paperboard Pads

On the basis of the family of dynamic cushioning curves of corrugated paperboard pads (**Figures 7 to 9**), these different static loads exerted on the bottom test specimen are respectively selected as follows: 1) For single layer pad, four kinds of different static loads, 2.178 kPa, 2.439 kPa, 3.049 kPa and 3.484 kPa; 2) For two layers pad, fourteen kinds of different static loads, 0.871 kPa, 1.132 kPa, 1.307 kPa, 1.568 kPa, 1.742 kPa, 2.178 kPa, 2.439 kPa, 2.613 kPa, 3.049 kPa, 3.920 kPa, 4.617 kPa, 4.791 kPa, 5.227 kPa and 5.662 kPa; 3) For three layers pad, eleven kinds of different static loads, 0.871 kPa, 1.307 kPa, 1.742 kPa, 2.178 kPa, 2.613 kPa, 3.049 kPa, 3.310 kPa, 3.484 kPa, 4.356 kPa, 4.791 kPa and 5.227 kPa. According to the test method ASTM D 4168, the vibration tests with slow sine sweep for corrugated paperboard pads at different static loads are made, and the vibration transmissibility and frequency curves are obtained. For example, **Figure 11** is the vibration transmissibility and frequency curve of single layer pad at static load 2.439 kPa, **Figure 12** gives that of two layers pad at static load 4.617 kPa, and **Figure 13** provides that of three layers pad at static load 4.791 kPa. Due to the limited space, other vibration transmissibility and frequency curves are omitted.

On the basis of these vibration transmissibility and frequency curves, resonance frequencies, vibration transmissibility and damping ratios are analyzed by using linear vibration theory with single degree of freedom, and the damping ratios (smaller than one) are estimated by using Equation (6). For example, **Table 2** gives the experimental results of single layer pad at static loads of 2.439 kPa and 3.049 kPa. **Table 3** provides that of two layers pad at static loads of 1.568 kPa, 2.613 kPa, 3.920 kPa, 4.617 kPa,

Table 1. Characteristic factors of dynamic cushioning curves.

Pad type	Drop height /cm	a_0, a_1, a_2, a_3
Single layer pad	30	464, -2132.9, 3014.3, 3325
	30	273.8, -632.6, -455.9, 2299.3
Two layers pad	60	122.58, 4071.8, -37339, 86990
	90	600, -8067, 48250, -69897
Three layers pad	30	344.2, -1796.3, 3717.5, -2400.1
	60	148.07, 1004.3, -7969.2, 13630
	90	190.4, -1103.5, 4217.2, 1792.7

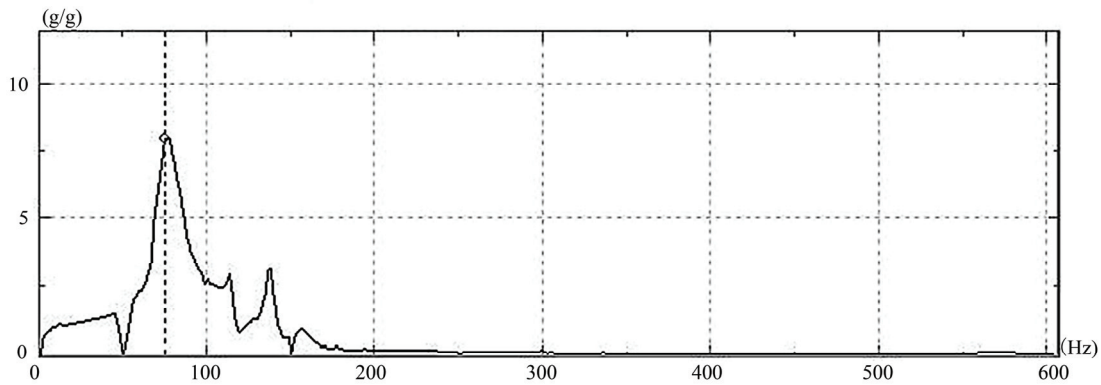


Figure 11. Vibration transmissibility and frequency curve of single layer pad.

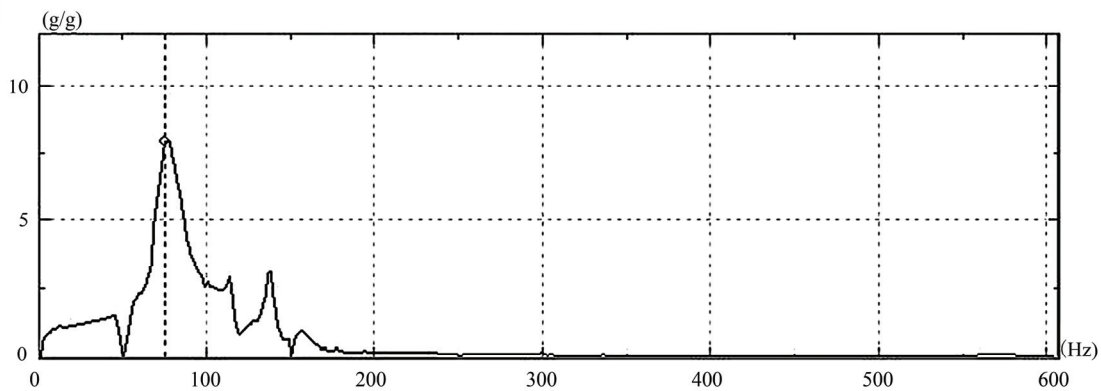


Figure 12. Vibration transmissibility and frequency curve of two layers pad.

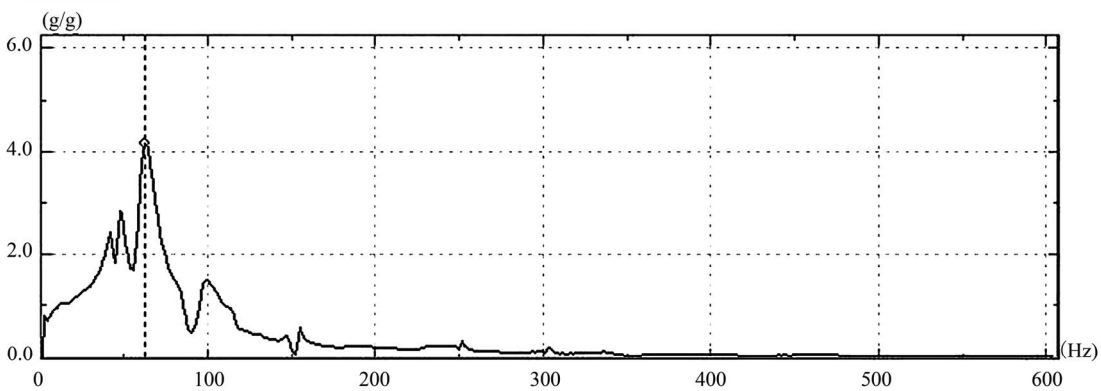


Figure 13. Vibration transmissibility and frequency curve of three layers pad.

5.227 kPa and 5.662 kPa. **Table 4** reflects that of three layers pad at static loads of 0.871 kPa, 2.178 kPa, 3.049 kPa, 4.791 kPa and 5.227 kPa. Due to the limited space, other experimental results are omitted.

By comparing and analyzing the experimental results and curves of vibration transmissibility of corrugated paperboard pads at different static loads, some conclu-

sions may be reached as follows:

1) The package cushioning system of corrugated paperboard pads has different resonance frequencies, yet only several resonance frequencies are primary and other resonance frequencies have a little effect on the packaged item during distribution. For instance, while static load 4.617 kPa is exerted on two layers pad, the vibration

Table 2. Vibration transmissibility of single layer corrugated paperboard pad.

Static load /kPa	Resonance Frequency /Hz	Vibration transmissibility	Damping ratio
2.439	12	0.995	
	73	1.364	0.539
	97	1.814	0.330
	132	8.031	0.062
	191	2.445	0.224
3.049	339	0.475	
	12	0.985	
	73	1.453	0.474
	97	1.966	0.295
	123	9.928	0.050
	189	2.206	0.254
	338	0.429	

Table 3. Vibration transmissibility of two layers corrugated paperboard pad.

Static load /kPa	Resonance Frequency /Hz	Vibration transmissibility	Damping ratio
1.568	14	1.014	
	91	1.615	0.394
	127	3.108	0.170
	167	11.214	0.045
	208	3.630	0.143
2.613	335	0.492	
	14	1.032	
	38	1.742	0.351
	85	3.271	0.161
	112	5.217	0.096
3.920	280	0.515	
	12	1.007	
	53	2.408	0.228
	88	7.893	0.063
	102	5.574	0.090
4.617	114	5.890	0.085
	293	0.680	
	12	1.038	
	45	1.416	0.499
	74	7.926	0.064
5.227	114	2.941	0.181
	138	3.121	0.169
	156	0.873	
	14	1.039	
	56	2.538	0.214
5.662	70	6.416	0.078
	106	1.601	0.400
	133	1.443	0.481
	153	0.458	
	14	1.090	
5.662	35	2.225	0.252
	55	2.805	0.191
	76	2.122	0.267
	97	1.077	
	121	0.425	

transmissibility and frequency curve (Table 3 and Figure 12) has six resonance frequencies such as 12 Hz, 45 Hz, 74 Hz, 114 Hz, 138 Hz and 156 Hz, their vibration transmissibility are 1.038, 1.416, 7.926, 2.941, 3.121 and 0.873, respectively. The vibration transmissibility at 74 Hz is about 9.08 times as much as that of 156 Hz, the vibration transmissibility at 138 Hz is about 3.58 times as

much as that of 156 Hz, so the resonance frequency 74 Hz should be taken as the first principle mode of vibration, resonance frequency 138 Hz as the second mode, etc. The result indicates an important guidance that the primary resonance frequencies must be avoided in package cushioning design of corrugated paperboard pads.

2) For the package cushioning system with corrugated paperboard pad, there is critical frequency at which the vibration transmissibility is high, and above the critical frequency the vibration transmissibility drops and is smaller than one. For example, the critical frequency of single layer pad is 191 Hz (Table 2). When the excitation frequency is higher than 191 Hz, the vibration transmissibility is very low, and the corrugated paperboard pad shall efficiently decrease vibration. In addition, for two layers pad, the critical frequency is 208 Hz (Table 3), and for three layers pad, the critical frequency is 185 Hz (Table 4). So the package cushioning system of corrugated paperboard pad may efficiently attenuate vibration with higher excitation frequency during distribution.

3) The static load exerted on the corrugated paperboard pad has an evident influence on vibration transmissibility. The influence relates to the mechanical behavior of corrugated paperboard, especially viscoelasticity. The result suggests another important guidance that the

Table 4. Vibration transmissibility of three layers corrugated paperboard pad.

Static load /kPa	Resonance Frequency /Hz	Vibration transmissibility	Damping ratio
0.871	14	1.024	
	71	1.500	0.447
	84	2.053	0.279
	112	3.286	0.160
	138	7.633	0.066
	185	2.191	0.256
2.178	332	0.725	
	14	1.045	
	61	3.969	0.130
	77	6.832	0.073
	106	3.823	0.136
3.049	127	1.288	0.616
	158	0.593	
	14	1.042	
	55	2.720	0.198
	74	4.744	0.108
4.791	103	2.321	0.239
	126	1.334	0.566
	152	0.387	
	14	1.061	
	41	2.423	0.227
5.227	54	2.852	0.187
	62	4.192	0.123
	98	1.511	0.441
	155	0.563	
	12	1.063	
5.227	47	3.482	0.150
	56	2.439	0.225
	82	2.303	0.241
	105	1.152	0.874
	130	0.550	

vibration transmissibility and frequency curve must be selected according to the static load exerted on it in package cushioning design of corrugated paperboard pads.

6. Conclusions

This research work obtains dynamic cushioning curves, vibration transmissibility and frequency curves of corrugated paperboard pads by a series of experimental studies, and evaluates its dynamic packaging properties relevant to its application for protective packaging such as dynamic shock cushioning property and vibration transmissibility. The waves of drop shock acceleration are similar to half-sine pulses, the shapes of dynamic cushioning curves are always concave and upward, and each piece of dynamic cushioning curves has only one minimum value point. The package cushioning system of corrugated paperboard pads has different resonance frequencies, and only several resonance frequencies are primary. The results show that corrugated paperboard pads possess dynamic shock cushioning property for drop shock, and the three layers pad has better dynamic shock cushioning property than single layer pad and two layers pad. For the package cushioning system with corrugated paperboard pads, there is critical frequency at which the vibration transmissibility is high, and above the critical frequency the vibration transmissibility drops and is smaller than one. The critical frequency of single layer pad is 191 Hz, that of two layers pad is 208 Hz, and that of three layers pad is 185 Hz. The package cushioning system of corrugated paperboard pad may efficiently attenuate vibration with higher excitation frequency during distribution.

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8. References

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