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Impact test and characteristic analysis of packaging materials

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Abstract: *In view of the problems existing in the current logistics transportation industry, such as long transportation distance, long time and large material flow. In order to effectively reduce the damage rate and transportation cost of packaging during transportation, virtual instruments are used as the data acquisition and processing platform, DY-2 impact testing machine is used as the platform for drop impact test, and a data acquisition system for drop impact test is built through multiple sensors, acquisition cards, adapters and other experimental equipment. The purpose is to study the cushioning effect and energy absorption effect of packaging materials through drop tests at different heights and thicknesses. The acceleration-stress curve is drawn through the collected data, and the energy absorption effect of packaging materials EPS is obtained through the waveform and trend of the curve. Through the method of controlling variables, after many drop impact tests, we find that the buffering characteristic curve of EPS is consistent with the classical packaging impact theory. The experimental results show that the data collection and processing methods are very standardized and accurate, which provides an important scientific basis for the design of buffer packaging.*

Keywords: *Drop Impact; Data Acquisition; Virtual Instrument; Least Squares Fitting*

1. Introduction

During transportation, packages are subject to strong shocks and collisions due to vibration. In order to simulate these impact effects, the impact load is applied to the buffer material by a free-falling mass block, that is, dynamic compression test. The dynamic characteristic curve of buffer material can be obtained by the test, which provides an important basis for packaging design. The design of buffer packaging needs to achieve the best economic benefits while ensuring safety, so the analysis and testing of buffer material properties is crucial. Most packaging buffer materials are nonlinear[1-2], and their stress and deformation curves are complex, which is difficult to analyze directly. With the development of science and technology, at present, in order to more accurately reflect the actual impact situation, many packaging designers use FFT analyzer or impact measuring instrument to obtain a more accurate buffer coefficient - maximum stress curve, maximum static stress curve and the corresponding acceleration curve[3-4], so as to better reflect the physical stress state. However, due to the secondary processing of the above method and the inability to obtain accurate acceleration curve, the difficulty of testing is increased[5], and the design cycle is increased. In order to solve these problems, Shan Jingmin[9] et al. developed a dynamic compression test system for buffer materials using VC++ platform, which can be used for data acquisition and analysis. The VC++ platform has a long development cycle, and it is difficult to adjust software modules in the changing test requirements. Therefore, this paper presents a buffer material characteristic test system based on virtual instrument technology, which can effectively realize the test and analysis of buffer materials. The data acquisition system collects information through acceleration sensors and stress sensors. Among them, the main purpose of the stress sensor is to measure the stress on the back of the material at the time of impact.

In logistics transportation, packaging goods involves multiple transfers using vehicles such as trucks, trains, and ships, as well as several manual or mechanical loading and unloading processes, along with multiple storage stacking stages. During the loading and unloading (handling) stages, factors such as human error or environmental conditions—like manual tossing or falling during lifting—can lead to the dropping and impact of packaged items. The acceleration of impact experienced by a product is determined by the height of the drop, while the intensity of the impact is influenced not only by the drop height but also by the product's weight, packaging[8,10] method, characteristics of cushioning materials, and the stiffness of the impact surface.

During transportation, actions like vehicle acceleration, changes in speed, steering, and braking can cause variations in velocity of the packaged items, resulting in mechanical collisions. The main factors leading to damage of packaging products during repeated use are impacts, vibrations, and similar forces.

Mechanical impact phenomena[12-13], such as the starting and emergency braking of vehicles, as well as the free fall of packaged items, release, transform, and transfer energy within a short impact duration, significantly affecting the safe operation of products and fragile components. The dynamic response analysis[16-17] of a box under impact loads primarily includes three aspects: (1) the dynamic response of the box under impact and vibration loads; (2) the transmission of vibrations and impacts from the box to the products[18]; (3) the dynamic response of the box and fragile components.

2. Buffer packaging material buffer characteristics theory

Through the free fall simulation, we can better describe the behavior of the package in the drop impact test, as shown in Figure 1.

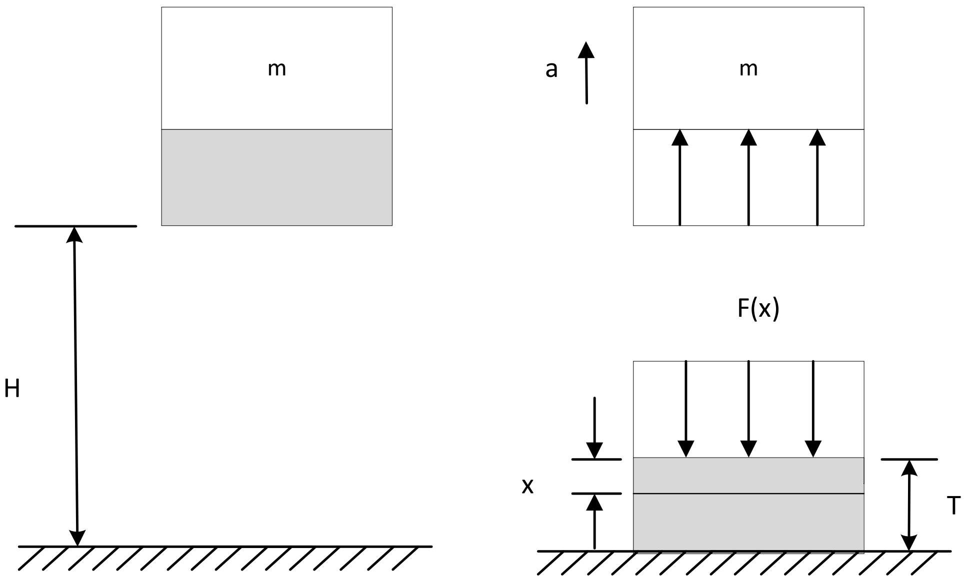

Figure 1: Dynamics model of drop impact process

In the drop test of the package, we adopted a method based on natural fall, converting all the compression energy into energy for the tensile strain of the buffer material, which is not affected by air resistance. The movement rule is:

$$\int_0^x \mathrm{F}dx + \frac{1}{2}mv^2 = W(H + x) \tag{1}$$

Because x=Tε:

$$\int_0^x \mathrm{F}dx + \frac{1}{2}mv^2 = \int_0^\varepsilon A\sigma T d\varepsilon + \frac{1}{2}mv^2 = AT\int_0^\varepsilon \sigma d\varepsilon + \frac{1}{2}mv^2 = W(H + x) \tag{2}$$

In the above formula:

m represents the mass of the weight, kg;

σ is the compressive stress that the specimen can withstand, and σ= F/A, Pa;

v is the speed of the mass block in the process of impacting the packaging material, m/s;

A represents the bearing area of the sample,m^2; F is the force acting on the buffer material,N;

W heavy weight,N; T is the thickness of the sample,m;

H Drop height of the heavy weight,m;

x is the compressive deformation of the sample,m;

ε is the compressive strain of the specimen and ε= x/T.

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According to Newton's second law:

$$F_m = W\frac{a_m}{g} \tag{3}$$

Let $G = \frac{a}{g}$:

thereupon

$$G_m = \frac{a_m}{g} = \frac{F_m}{mg} = \frac{A\sigma_m}{W} = \frac{\sigma_m}{\sigma_s} \tag{4}$$

In the above formula, F_m represents the force acting on the buffer material when the buffer material reaches the maximum deformation,N;

a is the addition of the weight in the impact process, m/s^2;

$a_m$is the maximum acceleration of the weight during the impact, m/s^2;

G_m is the maximum acceleration of the sample acting on the weight;

g is the acceleration of gravity;

σ is the static stress received by the buffer material, σ_s=W/A,Pa;

σ_m is the maximum stress on the buffer material, $\sigma_m = G_m\sigma_s$,Pa ;

The buffering coefficient C is the reciprocal of the buffering efficiency η. Its expression is:

$$C = \frac{1}{\eta} = \frac{FT}{e} \tag{5}$$

Where: e is the deformation energy of the sample, $e = \int_0^x Fdx$.

When the compression of the buffer packaging material reaches x_m, then the impact velocity of the weight v = 0, the energy brought by the impact load is completely converted into the required deformation energy e_m, obtained by formula (2) :

$$e_m = \int_0^{x_m} Fdx = \int_0^{\varepsilon_m} A\sigma T d\varepsilon = AT\int_0^{\varepsilon_m} \sigma d\varepsilon = W(H + x_m) \tag{6}$$

In the above formula, x_m represents the maximum deformation of the buffer material, and the unit is m.

By substituting equations (3),(4) and (6) into equation (5), the dynamic buffer coefficient C is obtained:

$$C = G_m\frac{T}{H+x_m} \tag{7}$$

3. Drop impact test system

3.1 System Principles

The drop impact test system is based on GB8167 "Dynamic compression Test Method for buffer Materials for Packaging". Design a drop impact measurement system with high efficiency, its core parts include: a drop impact measurement instrument, data acquisition card, PLC controller, acceleration sensor, voltage amplifier and a computer, as shown in Figure 2.

The PLC control box can control the rise and fall of the mass block to achieve the impact action of the impact testing machine. When the mass block is in contact with the buffer material, the stress sensor under the buffer material will transmit the voltage signal to the voltage amplifier, and collect the amplified signal to the data acquisition card, the data acquisition card can convert the collected analog signal into a digital signal, so as to realize the real-time monitoring of the impact testing machine. And can quickly and accurately detect the change of packaging materials during the impact of mass blocks, so as to better monitor the operating status of the system, improve the real-time and reliability of the impact test system. Through computer processing, we can present the data. Figure 3 depicts the operation of the drop impact test system.

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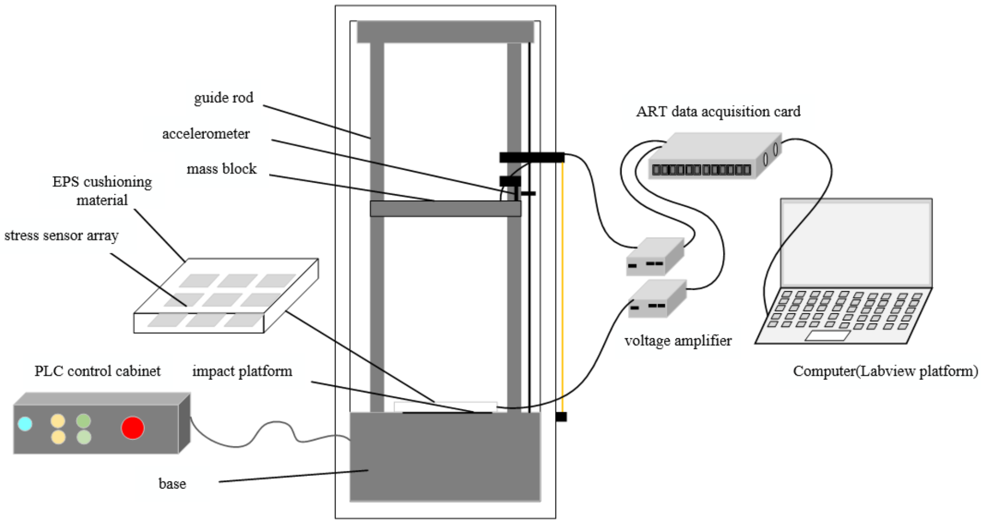

Figure 2: Architecture of the drop impact test system

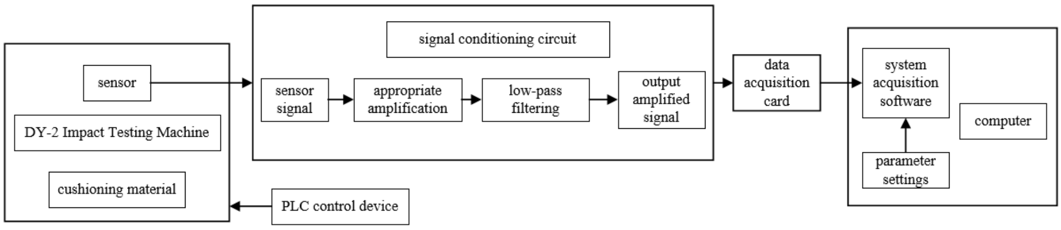

Figure 3: Schematic of the drop impact test system

The drop impact testing machine is connected with the PLC control equipment, and the action of the drop impact testing machine is controlled by the PLC control system. As the upper computer, the computer displays the sign a of the sensor collected by the acquisition card in real time. The original signal of the data acquisition card comes from the signal of multiple sensors, so the signal collected by the acquisition card displayed by the computer can reflect the impact state of the drop test in real time. By using the PLC control system, we can greatly improve the operating process of the testing machine, not only improve the operating accuracy, but also reduce human intervention, and further reduce the experimental error.

3.2 Acceleration signal acquisition and processing

Under the impact of the drop, the load will be absorbed by the buffer material EPS, but to accurately obtain the load, it is necessary to take into account the connection between the buffer coefficient of the buffer material and the acceleration of the force a, in order to accurately estimate the size of the load. Through the second-order low-pass filter, the current signal detected by the acceleration sensor is amplified and converted into A signal that can be processed by the computer. This signal can be converted into a signal that can be processed by the computer. This signal can be converted through the analog channel of the acquisition card and the cache of the acquisition card. This is ultimately converted into a signal that can be processed by a computer. By adopting a "limiter filter" two-stage filter, we are able to eliminate the signal from the voltage data with a residual 3σ (σ refers to the root-mean-square difference of the sampled data) to reduce the impact of large random interference. The Butterworth filter is used to propose signals greater than the cutoff frequency. Using the accuracy of the sensor and the efficiency of the voltage amplifier, we can convert the charge change into an acceleration (g) to obtain an acceleration-time series, and we can also use these parameters to estimate the buffer coefficient. The data collection process is shown in Figure 4.

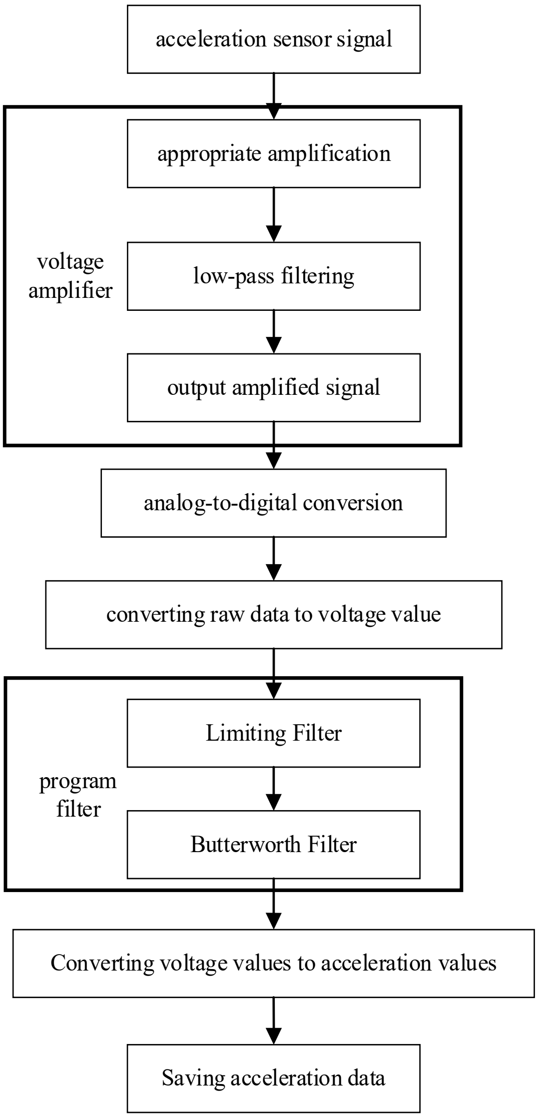

Figure 4: Data acquisition and processing

3.3 Compression deformation

In the process of drop impact, the compression deformation of packaging materials can allow the tester to analyze the buffer performance of buffer packaging materials more intuitively. The compression deformation of the sample x can be reflected by the displacement of the hammer in the impact process s, and its compression deformation is:

$$s = V_0 t + \int_0^t \left(\int_0^t a(t) dt \right) dt \tag{8}$$

Where: V_0 is the initial impact velocity, and the unit is m/s; t indicates the contact time between the weight and the buffer material, the unit is s; a(t) represents the acceleration of the weight during impact in m/s^2. Through the qualitative analysis of the compression deformation of the sample, the design of buffer packaging can be better evaluated and reliable scientific basis can be provided for it.

3.4 Buffer characteristic curve fitting

Most of the packing buffer materials are nonlinear, so the least square method is used to fit the data to determine the buffer coefficient - maximum static stress curve and maximum acceleration - static stress curve, and the relevant fitting equations can be accurately solved. By using these equations, we can quickly and accurately measure the size of buffer layer, which greatly reduces the time of searching resources, and also provides a powerful reference for the production of buffer layer.

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According to the data of a single test, a set of $(\overline{G_{mi}}, \sigma_{si})$ data is calculated by using the formula (4) and σ_s, where i represents the i test, and G_{mi} represents the average value of ,$\overline{G_{mi}}$ in the i test. Then, using the discrete data (x_i, y_i) for l+east square fitting, the acceleration-stress curve is obtained.

A set of discrete data (C_i, σ_{mi}), is obtained by using formula (7) and σ_m. The discrete data (x_i, y_i) are fitted by least square method, and the buffer coefficient - maximum static stress curve of buffer material is calculated. The smaller the buffer coefficient, the more energy absorbed by the packaging material per unit volume, indicating that the better the buffer performance. There is an inherent relation between the curve of maximum acceleration-static stress and the curve of buffer coefficient maximum stress, and the two curves can be converted to each other by formulas (5), (6) and (7).

4. Test

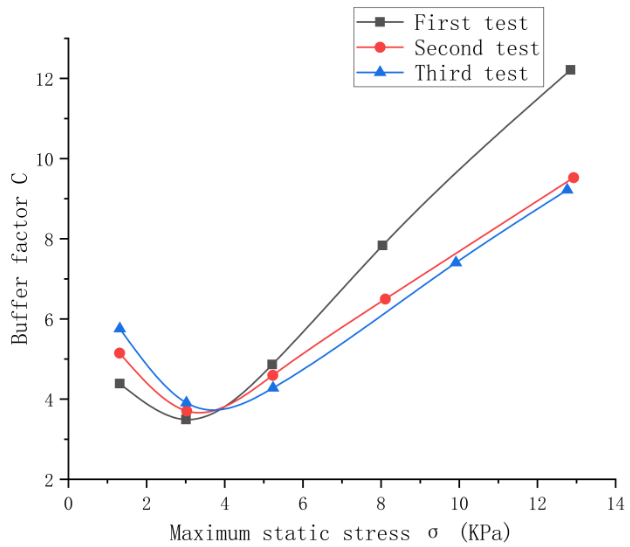
Impact test was carried out on the sample of EPS material (drop impact test parameters of EPS material are shown in Table 1). The buffer coefficient C and the maximum stress σ_m were calculated by formulas (4), σ_s,(7) and σ_m The specific values are shown in Table 2.

Table 1: Drop impact test parameters of EPS material

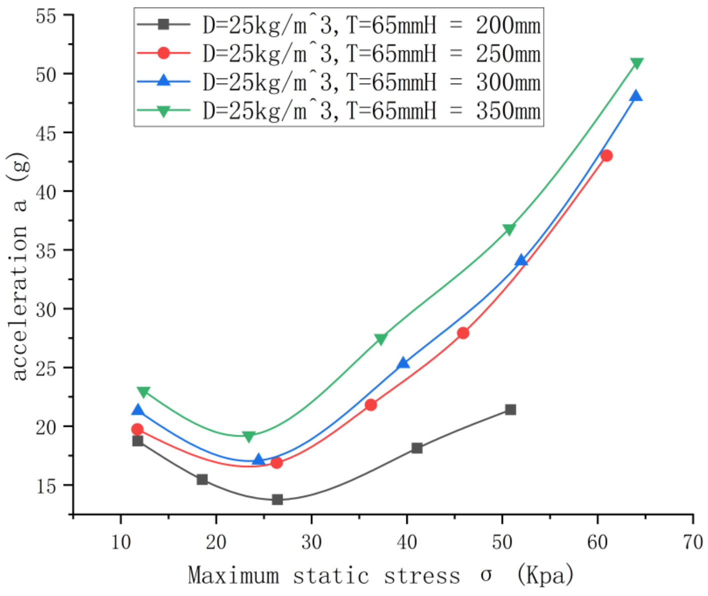
density $/(kg \bullet m^{-3})$	Length /m	breadth /m	thickness /m	Drop height /m
20	0.11	0.11	0.025	0.76

Table 2: Cushion coefficient and the largest stress of EPS material

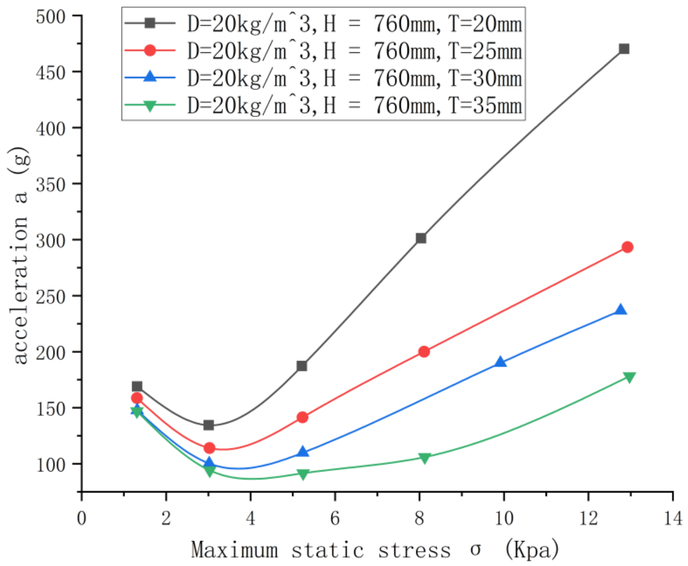
Number of experiments	Number of shocks	C	σ_m/KPa
First test	1	4.38734	1.313764
	2	3.49213	3.009653
	3	4.86306	5.215123
	4	7.83292	8.038941
	5	12.2134	12.84697
Second test	1	5.15106	1.309643
	2	3.70449	3.027532
	3	4.59621	5.227325
	4	6.49727	8.108301
	5	9.52592	12.92303
Third test	1	5.75805	1.314835
	2	3.90695	3.020961
	3	4.27971	5.234535
	4	7.40211	9.913294
	5	9.21935	12.76213



a. Buffer factor - maximum static stress curve



b. Maximum acceleration-static stress curves at different drop heights



c. Maximum acceleration-static stress curves at different thicknesses

Figure 5: Cushion characteristic curves of EPS material

Figure 5a shows the buffer coefficient and maximum stress curve of EPS packaging materials. The three curves are three tests conducted under the same conditions, and the maximum static stress and buffer coefficient are respectively obtained and calculated. The relative errors e_c and e_{σ_m} of the tests can be calculated by using instrument 1 and Table 2 as follows:

$$\begin{cases} e_c = \frac{C(i+1,j)-C(i,j)}{C(i,j)} \times 100\% \\ e_{\sigma_m} = \frac{\sigma_m(i+1,j)-\sigma_m(i,j)}{\sigma_m(i,j)} \end{cases} \tag{9}$$

The test data show that the maximum relative error between the buffer coefficients C is 0.97203%, while the maximum relative error between σ_m is 2.52854%, which indicates that the test results are good in terms of repeatability, but the large error of σ_m data may be caused by factors such as material structure changes or noise effects. Through the analysis of the sample T = 0.025m, it can be found from FIG. 1 that when the drop impact height H increases to a certain extent, the static stress curve of the H-buffer material will slow down and shift to the lower right. This situation can be explained by referring to the results of the first experiment in Table 2. This is because:

$$\begin{cases} (G_m T)_{min} = C_{min} H = \text{constant} \\ (G_m \sigma_s)_{\min} = (\sigma_m)_{min} = \text{constant} \end{cases} \quad (10)$$

Figure 5c is the measurement result of the maximum acceleration-static stress curve group under different specimen thickness T derived from the first test data in Table 2. As shown in FIG. 5c, the maximum acceleration-static stress changes with the increase of specimen thickness, and the curve gradually flattens and shifts to the right with the decrease of specimen thickness. As can be seen from formula (10), the curve first presents a stable situation, and then it will turn into an upward process. There is a pole on the curve where the buffering effect is the largest and the buffering performance is the best, which is consistent with the buffering performance of EPS. The experimental results show that the experimental data acquisition is standard, the waveform is complete, the fitting effect is good, and it has certain reference value for the design of buffer package.

5. Conclusion

Using the latest virtual instrument technology, a special drop impact test system for EPS materials is designed, which not only records and analyzes the drop impact process, but also explores the application value of the system in evaluating the performance of buffer packaging materials. After many tests, the experimental system has been fully proved its feasibility, and laid a solid foundation for the future buffer packaging design.

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