Hindawi Publishing Corporation
Shock and Vibration
Volume 2015, Article ID 462492, 7 pages
http://dx.doi.org/10.1155/2015/462492

Research Article

Shock Analysis on a Packaged Washing Machine from Damage Boundary: Shock Response Spectrum to Component Failure

Jing Qian,[1,2] Heping Cai,[1,2] Weiwei Ma,[1] and Zhiwei Hao[1]

[1] *Packaging Engineering Department, Jiangnan University, Wuxi, Jiangsu 214122, China*
[2] *Key Laboratory of Advanced Manufacturing Equipment Technology, Jiangsu 214122, China*

Correspondence should be addressed to Jing Qian; qj639@163.com

Received 29 July 2014; Revised 25 November 2014; Accepted 26 November 2014

Academic Editor: Ahmet S. Yigit

Both analyses of the damage boundary and shock response spectrum (RSR) are the basis for the development of the protective packaging system. The shock analysis through lab test and numerical simulation found that the root cause of packaging failure was due to the stress of the critical component beyond the yield limit of the material. Lab shock test data showed that the packaging design based on the damage boundary is conservative, and the RSR could be helpful and provide support to develop more effective packaging system. Furthermore, numerical simulation can accurately analyze the component and the entire product packaging system in great detail.

1. Introduction

Shock is a transient physical excitation and a mechanical shock is a sudden change in velocity and acceleration of an object caused, for example, by impact, drop, and kick. It is usually measured by an accelerometer and described as a shock pulse—a plot of acceleration change versus time. One of the packaging goals is to protect the product from damage caused by the mechanical shock.

In the 1970s, Dr. Newton [1] of Monterey Research Laboratory developed and validated the damage boundary concept at Michigan State University. Few years later, incorporated by the American Society for Testing and Materials (ASTM) into D3332 [2], the packaging industry was afforded a practical tool for determining the fragility of commercial products.

The damage boundary is normally expressed as a plot of peak acceleration versus velocity change, as shown in Figure 1 [3]. The vertical line, critical velocity change (ΔV_c), represents the velocity change which can be related to the drop height below which no product damage will occur, regardless of the peak acceleration. The horizontal line, critical acceleration (A_c), represents the acceleration and above at which the product will be damaged if velocity significantly exceeds ΔV_c.

Half-sine pulses are used to find the critical velocity change line (at which point the product breaks and must be repaired or replaced), and square wave pulses are used to find the critical acceleration line (breaking another product). The damage boundary theory, following D3332, has now been on the books for more than 40 years. It is widely accepted and this approach is taught and practiced in various forms worldwide.

From a practical standpoint, along with extensive use of the damage boundary, came the realization that package designs based solely on critical acceleration are sometimes quite conservative. The wave shape, which will be transmitted by the cushion, is essentially *never* a square wave, and the damage boundary *only considers* the input shock pulse; thus the whole packaging system is ignored. Therefore, an improved approach to relate product fragility and package performance is obviously needed.

The use of shock response spectrum (SRS) analysis may provide such an approach. SRS analysis calculates the responses of a large number of theoretical, single degree of freedom spring-mass systems to a given shock pulse. An SRS plot is a graph of the absolute value of the peak response accelerations of each spring-mass system, plotted at their various natural frequencies [4]. For the input from pulse

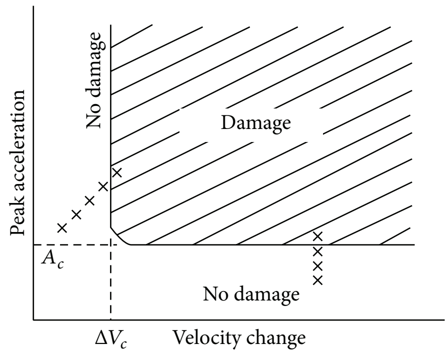


Figure 1: The damage boundary.

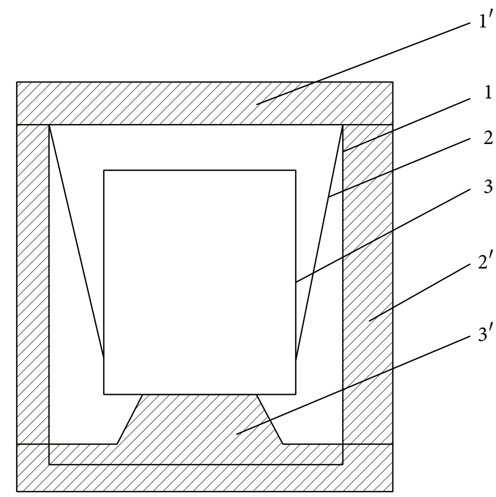


Figure 2: Cushion packaging of an impeller washing machine. 1: outer tank; 2: suspender; 3: washing tank; 1′: top cushion pad; 2′: corner holder; 3′: bottom cushion pad.

shock (shock table) that causes damage to the product, an SRS is calculated. This calculated shock response spectrum is called S_c, the "critical" SRS. Then S_c, rather than A_c, becomes the design target for protective packaging. When dropping from predetermined height, the SRS of the response shock pulse transmitted by the cushioning to product needs to lie below S_c.

From then on, many researchers worked on the theoretical analysis of the shock response of different linear or nonlinear cushioning packaging systems with various shock pulses [5–10], and the conducting study was graduated in depth from one-degree to three-degree systems [11–13]. Shock response spectrum is now wildly used in experimental tests considering not only shock condition but also vibration [14, 15].

In many cases, damage of products happened along structural elements, and damage of structural elements caused the failure of products. Suhir theoretically analyzed the shock and vibration responses of circuit boards of portable electronic products and found that the maximum dynamic stress is the key factor which caused the failure of the product [16]. The research on the packaging system of impeller washing machine gave a similar conclusion.

2. The Packaging System of the Washing Machine

An impeller washing machine is composed of a washing tank, a suspension system, and an outer tank. The suspension system is made up of four suspenders, which suspend the washing tank inside the outer tank which decreases transmitted vibrations from working washing tank. During the delivery, the washing machine is packed with a top cushion pad, a bottom cushion pad, and four corner holders (see Figure 2). At the center of the bottom cushion pad there is a raised bulge which can uplift the washing tank to release the suspension.

The cushion packaging (the cushion material, thick of crash pad, and so on) of washing machine was designed based on damaged boundary. Figure 3 shows the designed cushion mats.

In this research, the cushion material was polystyrene foam. The subsequent statistic data show that 20% damages came from a suspension system whose suspenders were straightened. The result confused engineers! Considering that the damage boundary does not include the whole cushion package, the researcher decided to find out not only the fragility of the washing machine but also the shock response of the packing system.

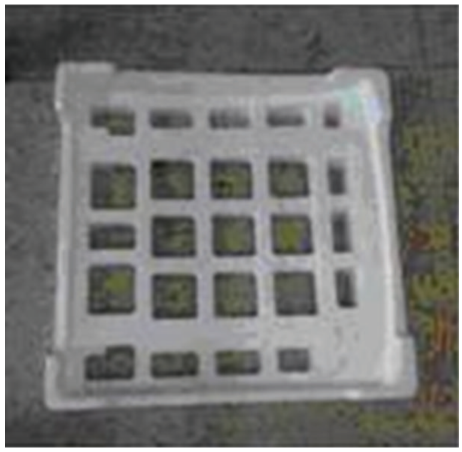
3. Shock Tests on Unpackaged and Packaged Washing Machine

Test equipment: MTS886.241 shock test system, Lansmont Test Partner 3 (TP3) data acquisitions system, and DASP data acquisition system.

The shock tests followed ASTM D3332-99, and the schematic diagram of the shock test is shown in Figure 4 [17]. During the test, the packaging case system of the washing machine was fastened to the shock table. Because the main protection is the bottom cushion pad, the other cushion pads were ignored in the test. Two accelerometers were used, one fastened to the shock table and the other at the bottom center of washing tank to record the input shock pulse and the response of washing machine, respectively. The two different data acquisition systems have their own accelerometers, and they were in pairs fixed very close to make sure each pairing gets almost the same signal.

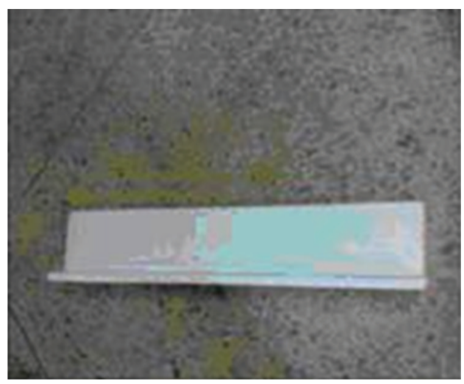
To confirm that the two data acquisition systems could give same recordings, a field test was set up, and the acquired signals from two channels were shown in Figure 5. In the tests, half-sine shock pulse was provided by a wave generator provided.

As shown in Figure 5, the maximum acquired accelerations were 908.023 m/s^2 (from DASP) and 902.87 m/s^2 (from TP3), respectively. The difference of two systems is 0.6%. Both intervals of two peak accelerations from two different systems are 0.1 s. Therefore the records from the two systems are much close to each other.



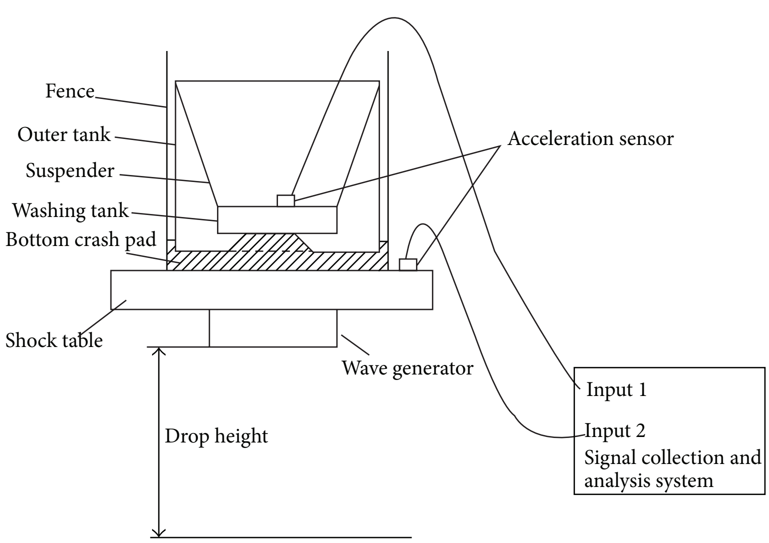
(a)

(b)



(c)

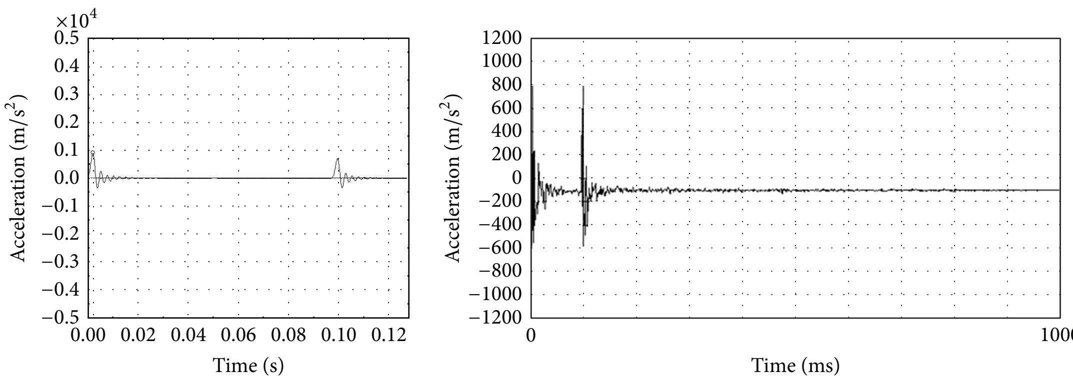
Figure 3: Cushion mats on the washing machine. (a) Top cushion pad; (b) bottom cushion pad; (c) corner holder.



(a) Schematic diagram

(b) Test photo

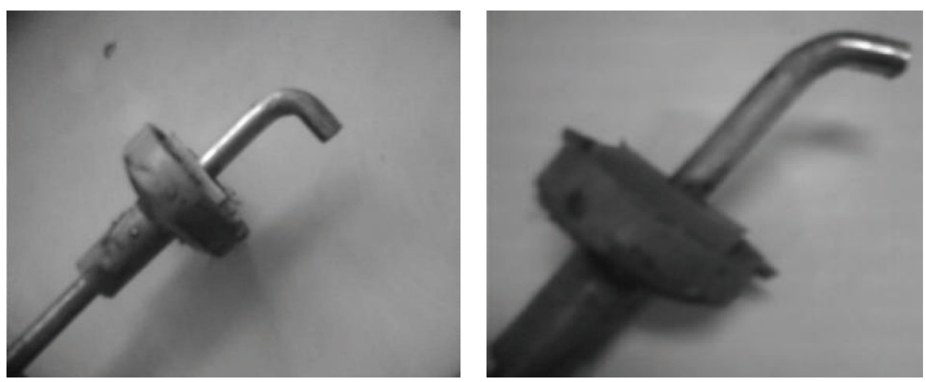
Figure 4: Shock test on washing machine packaging system.



(a) DASP

(b) TP3

FIGURE 5: Acquired signal on the 50 mm drop height.



(a) Normal

(b) Straightened

FIGURE 6: Suspender.

3.1. Shock Tests on Unpacked Washing Machine. In this section, the washing machine was fastened directly to the shock table without any cushion pads. The half-sine pulse was set up as an input shock pulse to the shock table. Shock tests started from 50 mm drop height. Increasing the drop height, one of the suspenders was straightened as shown in Figure 6 when the drop height reached 150 mm. The shock test at the 150 mm drop height was repeated twice; the test found that two suspenders were straightened each time.

Table 1 gives the maximum accelerations acquired from different channels at various drop heights. Normally the accelerations were recorded as multiples of the gravitational acceleration (G).

The fragility of the washing machine is normally between 90 G and 120 G as cited in MIL-HDBK-304 [18]. From Table 1, it is clear that the product is still safe even when the acceleration of the input pulse reached 152.3 G. The suspenders failed only when the input acceleration reached 171.6 G. Thus the package design, as based solely on the damage boundary, is quite conservative.

TABLE 1: Maximum accelerations acquired from different channels on the unpacked product.

Drop height (mm)	Input accelerations (G) (shock table)	Response accelerations (G) (center of washing tank)
50	90.8	2.40
70	114.3	2.92
100	138.2	5.00
120	152.3	12.74
150 (failure)	171.6	15.01

3.2. The Shock Test on the Packed Washing Machine. A half-sine pulse was provided as an input shock pulse to washing machine with the bottom cushion pad fastened to the shock table. Shock tests began at a 150 mm drop height. The drop height was increased until 400 mm when one straightened suspender failed. The shock tests were repeated twice at a 400 mm drop height. Two suspenders were straightened and the bottom cushion pad was damaged (see Figure 7) each time.

Table 2 shows the maximum accelerations acquired from different channels at various drop heights. Multiples of the gravitational acceleration were used to express the maximum acceleration.

As shown in Table 2, the packaged washing machine was intact even when the input acceleration reached 221.3 G.

Figure 7: The broken bottom cushion pad after the shock test at a 400 mm drop height.

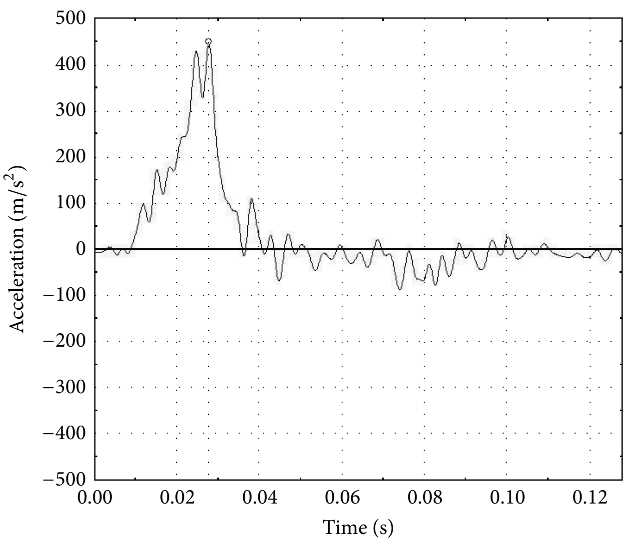


Figure 8: The response acceleration curve at a 400 mm drop height via DASP.

Table 2: The maximum accelerations acquired from different channels on packed product.

Drop height (mm)	Input accelerations (G) (shock table)	Response accelerations (G) (center of washing tank)
150	175.2	25.3
250	190.4	29.5
350	221.3	36.9
400 (failure)	244.1	44.8

Figure 8 shows the response acceleration curve at a 400 mm drop height of the packaged washing machine.

The acquired data were processed using the SRS analysis via the ETC module of TP3. The positive SRS curve of the packaged washing machine was achieved as shown in Figure 9. It clearly shows that the maximum acceleration of washing machine packaging system is 114.32 m/s^2 when the frequency is 835.42 Hz. The SRS curve could be the "critical" SRS of this packaging system. Each point on the SRS curve represents the critical acceleration S_c for the corresponding frequency. In other words, when the packaging system is delivered and the response acceleration is below the critical

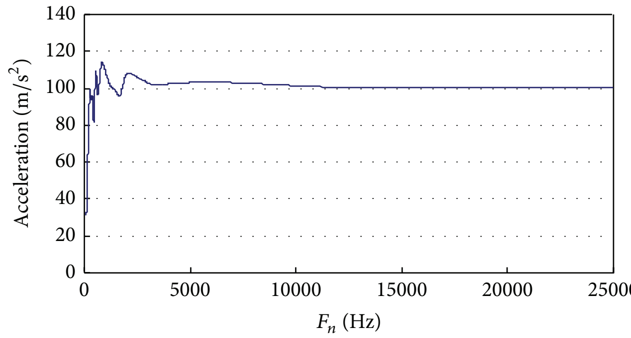


Figure 9: The positive SRS curve.

acceleration, S_c at every corresponding frequency, then the washing machine is safe.

4. Numerical Computation on Key Structural Elements of the Washing Machine

Each product has its weakest element which is the easiest to be damaged during transport. The weakest element in the packaging system is called the critical element. Based on the statistical data and the aforementioned research, the critical element of the washing machine is its suspenders. Actually, the damage of suspenders is plastic deformation, and this damage essentially happened because the stress of the critical element is beyond the allowable stress (yield strength) of the material. In this case, the numerical computation via ANSYS/LS-DYNA finite element software was used to see what happened as the drop height approached 400 mm.

4.1. The Development of the Computer Model on the Packaging System. The computer model of the washing machine packaging system [19] is composed of the washing tank, the outer tank, four suspenders, and cushion pads as shown in Figure 10. The properties of the materials are listed in Table 3.

Following Chinese national standard GB/T 8168-2008 [20], the compression test on the cushion material (EPS) was performed on the LRX Plus Universal Material Testing Machine. The stress-strain curve is shown in Figure 11.

To verify the viability of the developed model, the shock on the unpackaged washing machine was simulated by ANSYS software. Figure 12 shows the plot of acceleration versus time when the shock happened at a 50 mm drop height. Node A is on the bottom-center of the washing tank (the location of accelerometer for the shock test as shown in Figure 4), and node B is on the middle of washing tank. The acceleration-time history of node A agreed well with that obtained by shock table apparatus.

The maximum acceleration of node A is 23.8 m/s^2. By comparing with shock test data in Table 1, the response acceleration is 2.4 G (23.52 m/s^2) when the drop height is 50 mm. The error of simulation is 1.2%, and the developed model has sufficient accuracy. By comparing with node A and node B, it is clear that the peak acceleration of node B is smaller and lags slightly behind node A as shown in Figure 12.

Table 3: Properties of materials.

Part name	Material	Elastic modulus (GPa)	Density (Kg/m^3)	Poisson's ratio
Suspender	Q345	210	7850	0.3
Outer tank	08F	205	7850	0.3
Washing tank	PP	1.06	910	0.40–0.43
Spring	65Mn	/	/	/
Cushion pad	EPS	0.8	20	0.1
Ground	Rigidity	210	7850	0.2

Figure 10: The computer model of the washing machine packaging system.

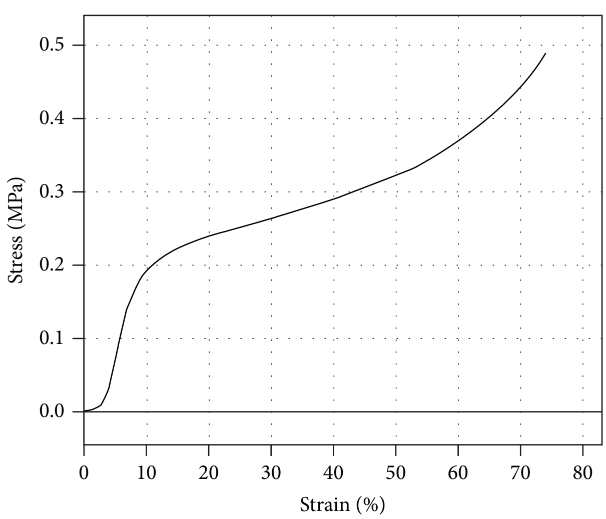


Figure 11: The stress-strain curve of the cushion material.

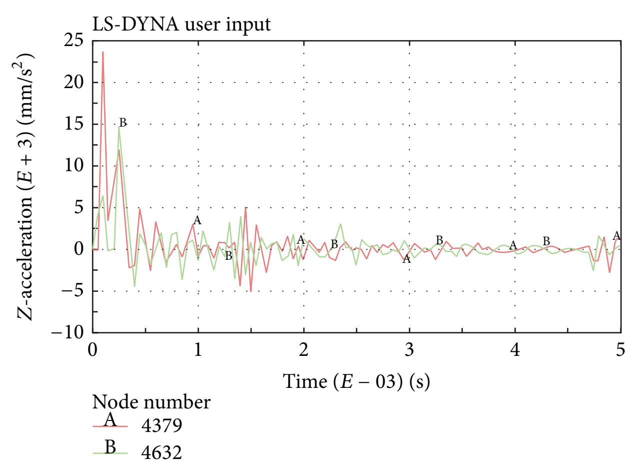


Figure 12: The acceleration response of the washing tank on different nodes for a 50 mm drop height.

Using the developed model of the packaged washing machine, the results of the simulation focus on the stress condition of the suspender. Figure 13 shows the change of axial force on suspender node 12055, which is proximal to the outer tank, when the drop height is 350 mm. Node 12055 is the point where the maximum axial force happened.

When the drop height is 350 mm, the maximum axial force of the suspender is 15.4 kN. The cross sectional area is 50 mm^2, so the axial stress is 308 MPa. Actually the suspender is a real pull rod, so the axial stress of suspender is a von Mises stress. The yield limit of Q345 (material of suspender) is 345 MPa. The computation result is very close to the yield limit of the suspender. Table 4 shows the maximum axial stress of the suspender when the equivalent drop height is close to 350 mm.

Table 3 shows that when the drop height reaches 360 mm, the axial stress of the suspender is beyond the yield limit of the material, and plastic deformation will happen; for example, the suspender will be straightened. The computational results match the results of the shock tests on the washing machine packaging system.

5. Conclusion

The research discussed shock tests and computer simulation to figure out the real reason that leads to damage of the critical element of the impeller washing machine packaging system.

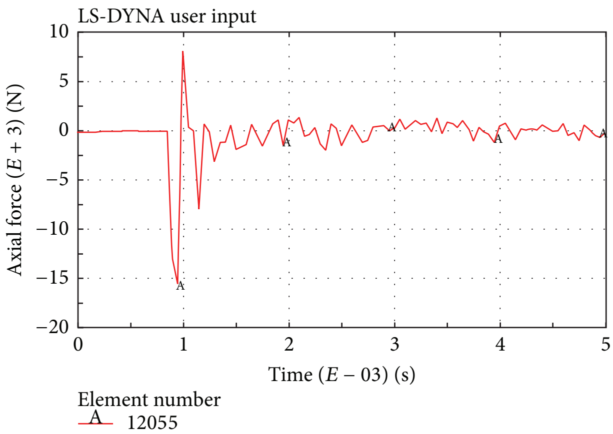


Figure 13: The axial force of suspender node 12055.

Table 4: The axial stresses of the suspender with different drop heights.

Equivalent drop height (mm)	The maximum axial stress of the suspender (MPa)
360	355
350	308
340	290

The stress of the critical component beyond the yield limit of the material is the root cause. Packaging design based on the damage boundary of the product is quit conservative, and the shock response spectrum could be more reliably used for packaging evaluation and design—the SRS of response acceleration transmitted by cushioning to the product must be below the critical acceleration S_c at every corresponding frequency. Hence numerical simulation can be used as a reliable tool and provide more detailed analysis of the product packaging system.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This research was supported in part by the Fundamental Research Funds for the Central Universities and Six Talent Peaks Funding from Jiangsu Province.

References

[1] R. E. Newton, *Fragility Assessment Theory and Test Procedure*, Monterey Research Laboratory, Monterey, Calif, USA, 1968.

[2] American Society for Testing and Materials, "ASTMD3332, standard test methods for mechanical shock fragility of products, using shock machines," in *Annual Book of ASTM Standards*, vol. 15.09, 2010.

[3] W. I. Kipp, "Developments in testing products for distribution," *Packaging Technology and Science*, vol. 13, no. 3, pp. 89–98, 2000.

[4] W. I. Kipp, "PSD and SRS in simple terms," in *Proceedings of the International Safe Transit Association Conference (ISTA '98)*, Orlando, Fla, USA, 1998.

[5] Z. Wang, D. Wu, and J. Qian, "The shock response of tangential nonlinear packaging system under the action of rectangular pulse," *Journal of Vibration and Shock*, vol. 18, no. 3, pp. 48–52, 1999.

[6] Z. Wang and G. Xiaoting, "The shock characteristics of hyperbolic tangent packaging system under the action of half-sine pulse," *Packaging Engineering*, vol. 2, no. 20, pp. 4–7, 1999.

[7] X. Gong and Z. Wang, "The shock characteristics of hyperbolic tangent packaging system under the action of rectangular pulse," *Packaging Engineering*, vol. 20, no. 3, pp. 12–15, 1999.

[8] J. Wang, F. Duan, J.-H. Jiang, L.-X. Lu, and Z.-W. Wang, "Dropping damage evaluation for a hyperbolic tangent cushioning system with a critical component," *Journal of Vibration and Control*, vol. 18, no. 10, pp. 1417–1421, 2012.

[9] J. Wang, Y. Khan, R.-H. Yang, L.-X. Lu, and Z.-W. Wang, "Dynamical behaviors of a coupled cushioning packaging model with linear and nonlinear stiffness," *Arabian Journal for Science and Engineering*, vol. 38, no. 6, pp. 1625–1629, 2013.

[10] A.-J. Chen, "The shock characteristics of tilted support spring packaging system with critical components," *Shock and Vibration*, vol. 2014, Article ID 496035, 8 pages, 2014.

[11] E. Suhir, "Dynamic response of a one-degree-of-freedom linear system to a shock load during drop tests: effect of viscous damping," *IEEE Transactions on Components Packaging and Manufacturing Technology Part A*, vol. 19, no. 3, pp. 435–440, 1996.

[12] V. P. Sergey, "Optimal protection of two-degree-of-freedomsystem from shock and vibration," in *Proceedings of International Conference Physics and Control*, vol. 4, pp. 1206–1208, IEEE, Saint Petersburg, Russia, 2003.

[13] J. Wang, Z.-W. Wang, L.-X. Lu, Y. Zhu, and Y.-G. Wang, "Three-dimensional shock spectrum of critical component for nonlinear packaging system," *Shock and Vibration*, vol. 18, no. 3, pp. 437–445, 2011.

[14] T. S. Edwards, "Power delivered to mechanical systems by random vibrations," *Shock and Vibration*, vol. 16, no. 3, pp. 261–271, 2009.

[15] S. Goyal, J. M. Papadopoulos, and P. A. Sullivan, "Shock protection of portable electronic products: shock response spectrum, damage boundary approach, and beyond," *Shock and Vibration*, vol. 4, no. 3, pp. 169–191, 1997.

[16] E. Suhir, "Is the maximum acceleration an adequate criterion of the dynamic strength of a structural element in an electronic product?" *IEEE Transactions on Components, Packaging, and Manufacturing Technology, Part A*, vol. 20, no. 4, pp. 513–517, 1997.

[17] W. Ma, *The cushion packaging of washing machine based on shock response spectrum [M.S. thesis]*, Jiangnan University, 2008.

[18] MIL-HDBK-304, *Department of Defense Handbook: Package Cushioning Design*, 1997.

[19] Z. Hao, *Dropping simulation analysis on key element of impeller washing machine [M.S. thesis]*, Jiangnan University, 2009.

[20] GB/T 8168-2008, *Testing Method of Static Compression for Packaging Cushioning Materials*, China National Standard, 2008.