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RESEARCH ARTICLE

Proposal of Hybrid Damping Package Design

Qi Zhang
Kobe University
cho@tsk-corp.jp

Katsuhiko Saito
Kobe University
ksaito@maritime.kobe-u.ac.jp

Katsushige Nagaoka
TSK Corporation
nagaoka@tsk-corp.jp

ABSTRACT

To protect products from shock and vibration during transport, Cushioning Packaging Design is implemented. The cushioning performance and anti-vibration performance of a package is tested by a drop test and a vibration test. The effectiveness of the cushioning during a drop test is predictable because the cushioning material`s thickness and bearing area are determined by the cushion curves which are plotted based on the results of the tests. However, an effective package-design method which can predict the package vibration of all the static stresses that are suitable for cushioning package design has not been established yet.thus, it remains uncertain until actually vibration tests are conducted and redesigns are developed to correct the failures during the tests. Redesigning efforts are expensive and time consuming. Therefore, in this study, we propose the "Hybrid Damping Package Design" wherein both the Cushioning Packaging Design and the Anti-vibration Package Design will be implemented. In particular, Multibody Dynamics simulation is applied as an aided design tool for Anti-vibration Package Design so that numerical analysis a package's vibration response becomes possible. Furthermore, we discuss a case study to demonstrate how to analyze and compare multiple package designs in order to determine the best candidates based on cushioning performance, anti-vibration performance, and material cost

KEY WORDS

cushioning package design, vibration simulation, multibody dynamics, anti-vibration package design, vibration test

1.0 INTRODUCTION

Protecting products from shock and vibration during transport has been an engineering problem for a long time. The traditional method of designing cushioning packaging is widely used to protect products from shock hazard; however, that method is unable to give sufficient consideration to vibration hazard. Nowadays, many troubles are caused by vibrations during transport, such as resonance, abrasion damage, and pinholes. These have been increasingly reported as the trend to minimize package size and cost.It is necessary to develop a new package-design method that can give consideration to both shock and vibration during transport. Therefore, we propose a new package-design method called "The Hybrid Damping Package Design," which is able to analyze and improve the results from a vibration test via digital simulation. Here, Damping indicates Cushioning and Anti-vibration, in which Cushioning means absorbing the shock energy from package's free fall during package handling etc. and Anti-vibration means absorbing the vibration energy from vibration caused by vehicle vibration etc. A case study is discussed to illustrate to how to use the proposed method to design packages, and the results demonstrate that the method is more efficient and accurate than the traditional one.

Two methods of digital simulation are mainly used in the package design field: the Finite Element Method (FEM) and Multibody Dynamics method. The FEM is relatively difficult to implement and a designer might not be able to master it in a short term. One of the reasons is that the procedure used to identify the parameters of the packaging material properties is still not clear, and designers need to be very experienced to develop simulated numerical solutions that match actual experimental results. As a system used in regular business, the FEM must become a more user-friendly system. Conversely, the Multibody Dynamics method uses relatively simple models in which some significant components are considered for a packaging system: (1) the continues product mass is approximated as a lumped equivalent mass, and (2) the cushioning material is approximated as a combination of springs (storing energy) and dampers (gradually losing energy). Whenever the design time is short for package designers, they widely use the Multibody Dynamics method because it is able to generate models much more simply, and the utilization is more convenient and user-friendly. Therefore, for our research, the Multibody Dynamics simulation was used.

The Multibody Dynamics method has been used to analyze various shock and vibration problems such as the transient response to step and pulse functions, and the dynamic vibration absorber[1]. As an application in the packaging field, (Wang Z *et al.)* suggested a general approach to obtain the shock spectra and damage boundary curves for cushioning package system[2]. (Rouillard V *et al.*) developed a model to predict the dynamic response of a stacked package system[3]. (Zhong *et al.*) developed a new drop test method using a simulation to predict the peak response acceleration of a test product[4]. (Matthew J. Lamb *et al.*) suggested a reverse multiple input/single output (RMISO)-based technique, which allows

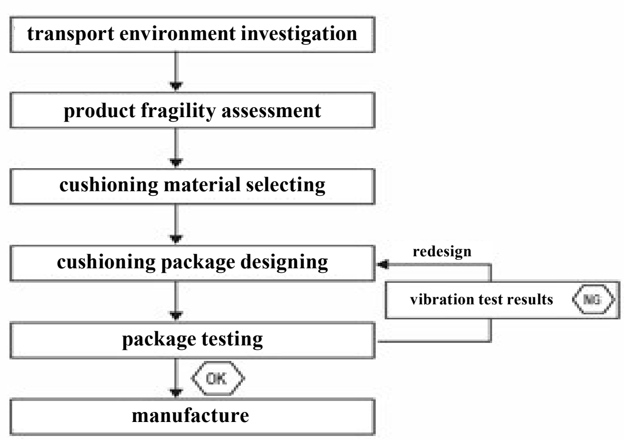

Figure 1: A simplified flowchart of the traditional cushioning package design.

traditional modal parameter-extraction techniques to be used for the analysis of a non-linear cushioning system[5]. However, these research efforts have contributed to either cushioning package design or anti-vibration package design separately. In this study, a new package-design method is proposed that considers both design challenges.

2.0 DAMPING PACKAGE DESIGN

2.1 The Traditional Cushioning Package Design

A simplified flowchart of the traditional cushioning package design is illustrated in *Fig.1*. The package testing step includes the drop test and the vibration test. The result of the drop test is predictable; however, an effective package-design method which can predict the package vibration of all the static stresses that are suitable for cushioning package design has not been established yet. Therefore, if the result of the vibration test exceeds the criterion for vibration fragility of the provided product, then the packaging must be redesigned, which means the cushioning package designing must be conducted again. Because redesign costs a lot of time and money, how to reduce the redesign effort is a realistic concern.

2.2 The Hybrid Damping Package Design

To reduce the redesigning effort, as mentioned in 2.1, we propose the Hybrid Damping Package Design as charted in *Fig.2*.

The main difference of the proposed method from the traditional one is that cushioning package design and anti-vibration design are conducted together. Therefore, the results of both the drop test and the vibration test are predictable, which effectively avoids the need for redesigning.

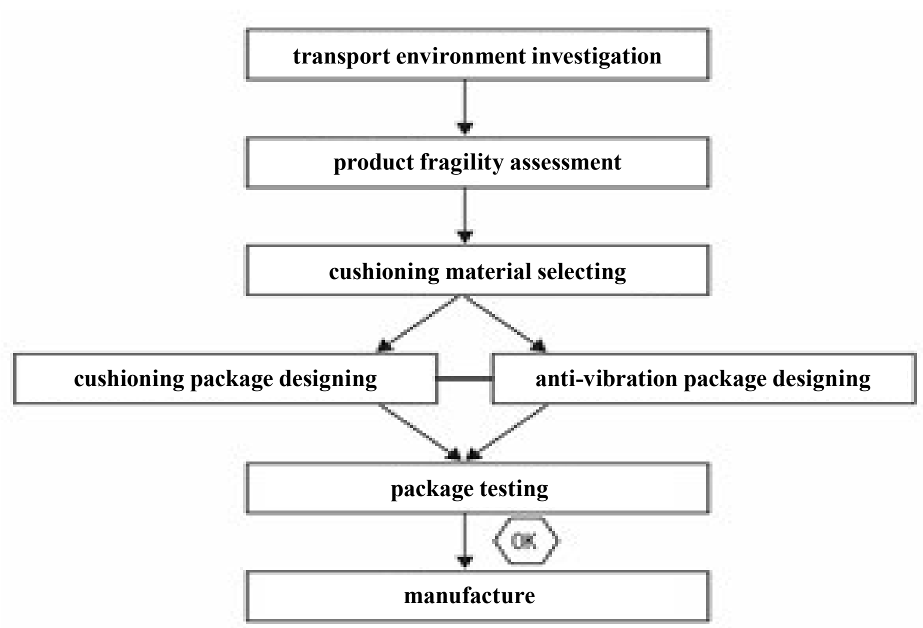

Fig. 2: The simplified flowchart of the Hybrid Damping Package Design[6].

3.0 HYBRID DAMPING PACKAGE DESIGN

3.1 The Multibody Dynamics Method

One of the advantages of the Multibody Dynamics method is that it uses relatively simple models to confirm the behaviors of complicated structures. It is widely used in the automobile field, and its practical analysis abilities have been really helpful during development and design stage[7].

Fig.3 shows the model examples of a two-layer, stacked, cushioned package. *Fig.3* (a) shows that two cushioned packages with some small parts inside are stacked as two layers and the one on the top is able to jump up. This system is considered as a single-degree-of-freedom (SDOF) system. *Fig.3* (b) shows a model with mass eccentricity. Even though the input of the system is uniaxial, the motion of the system would be expanding to be multiaxial. In addition, (Wang *et al.*) developed the refrigerator-truck system in which the package units between a refrigerator and a truck are composed of a set of coupling springs with damping[8]. (Rouillard *et al.*) developed a model of a stacked package system in which many masses are stacked up and every two masses connected by a spring and a viscous damper[3].

As part of the research of applying Multibody Dynamics to package design, a simple model of cushioned package is to be discussed. *Fig.4* shows the model used in this paper, which is called the viscous damp model (VD model). According to Zhong[9], the VD model shows a more realistic dynamic behavior due to the attenuation phenomenon being considered.

3.2 The Flowchart of Hybrid Damping Package Design

The Flowchart of Hybrid Damping Package Design is illustrated in *Fig.5.* First, the type, thickness, and bearing area of the cushioning material are

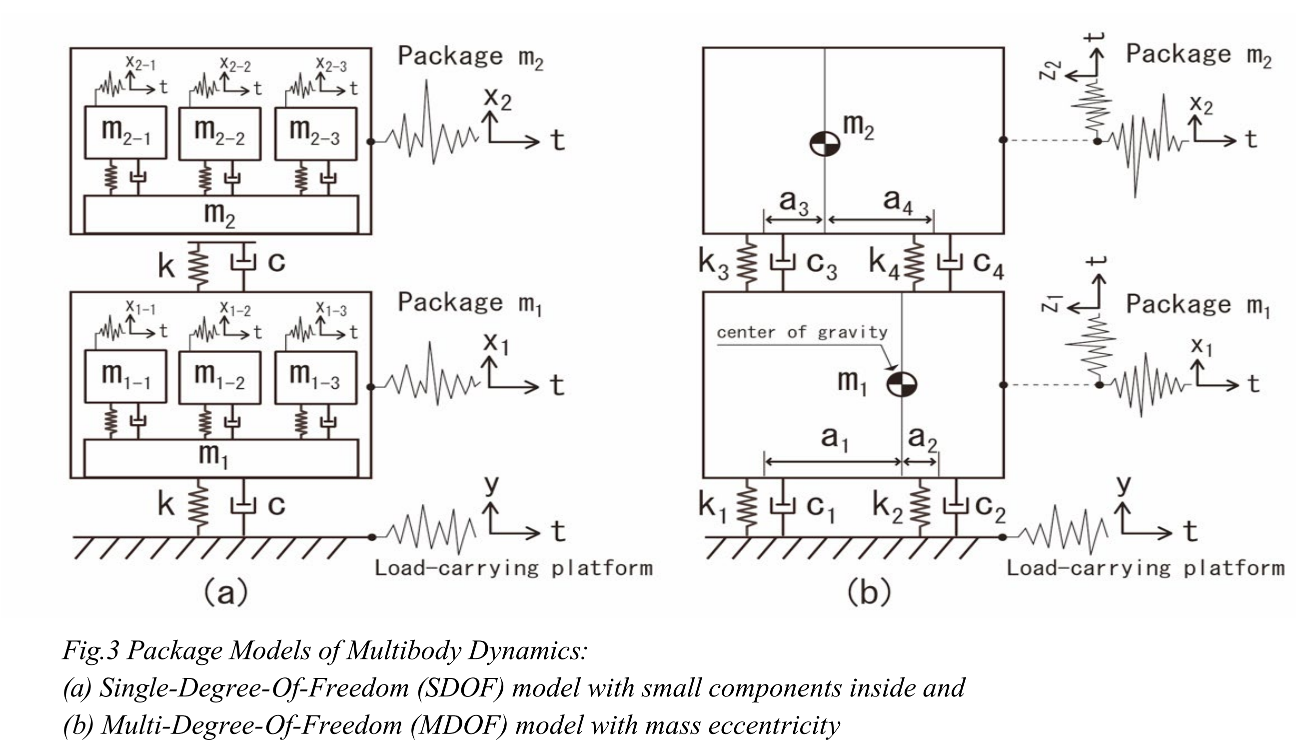

Fig.3 Package Models of Multibody Dynamics:
(a) Single-Degree-Of-Freedom (SDOF) model with small components inside and
(b) Multi-Degree-Of-Freedom (MDOF) model with mass eccentricity

initially determined by the cushion curve which is plotted from the results of the dynamic shock cushioning test performed using the traditional method. Second, the static stress–strain curve is used to calculate the cushioned package's spring constant *(k)* and input the *k* into a free-fall simulation. Then, using the dynamic stress–strain curve to tune the damping coefficient *(c)*, *k* and *c* are inputted into the random vibration simulation to predict the vibration response of the package. Finally, the results of the simulation are compared with the design conditions. If the result of the simulation does not meet the design conditions, a redesign effort should be conducted. Therefore, the merit of this method is that it enables package designers to obtain the optimal static stress for a package design without conducting the actual vibration tests upon package samples.

4.0 CASE STUDY

4.1 Design Condition Setting

To illustrate how to use the flowchart of the Hybrid Damping Package Design and verify the validity of the method proposed here, a case study is provided as follows:

4.1.1 Assumed Transport Environment

1) Shock:
   Drop height H: 60 centimeters (cm)
2) Vibration:
   Described by the power spectral density (PSD) curve in *Fig.6*.

4.1.2 Test Equipment and Materials

1) Equipment:
   Vibration machine (i210/SA1M made by IMV Corporation)
   Data Recorder (DER1000 made by Shiyei Testing Machinery Co., Ltd.)
   Sampling rate:1024 samples per second
   Full scale: 50 G
2) Test materials:
   Weight dummy *(Fig.7)*:
   Mass: 4 kg
   Shock fragility: 60 G
   Assumed Vibration fragility:
   root-mean-square of g-value (Grms),
   Grms =1.5 G.
   Material: wood
   Cushioning material
   Expanded polyethylene (Eperan™ XL38 made by Kaneka Corporation)
   Apparent density: 0.025g/cm³ (Expansion rate: 38)

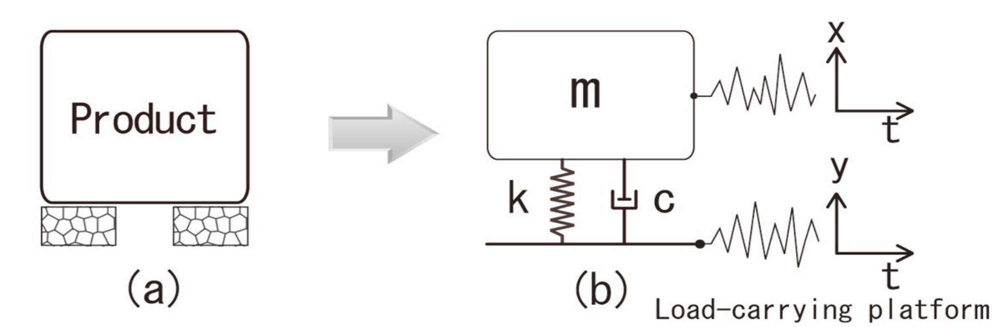

Fig.4 The viscous damp model (VD model): (a) Cushioned Package and (b) VD model.

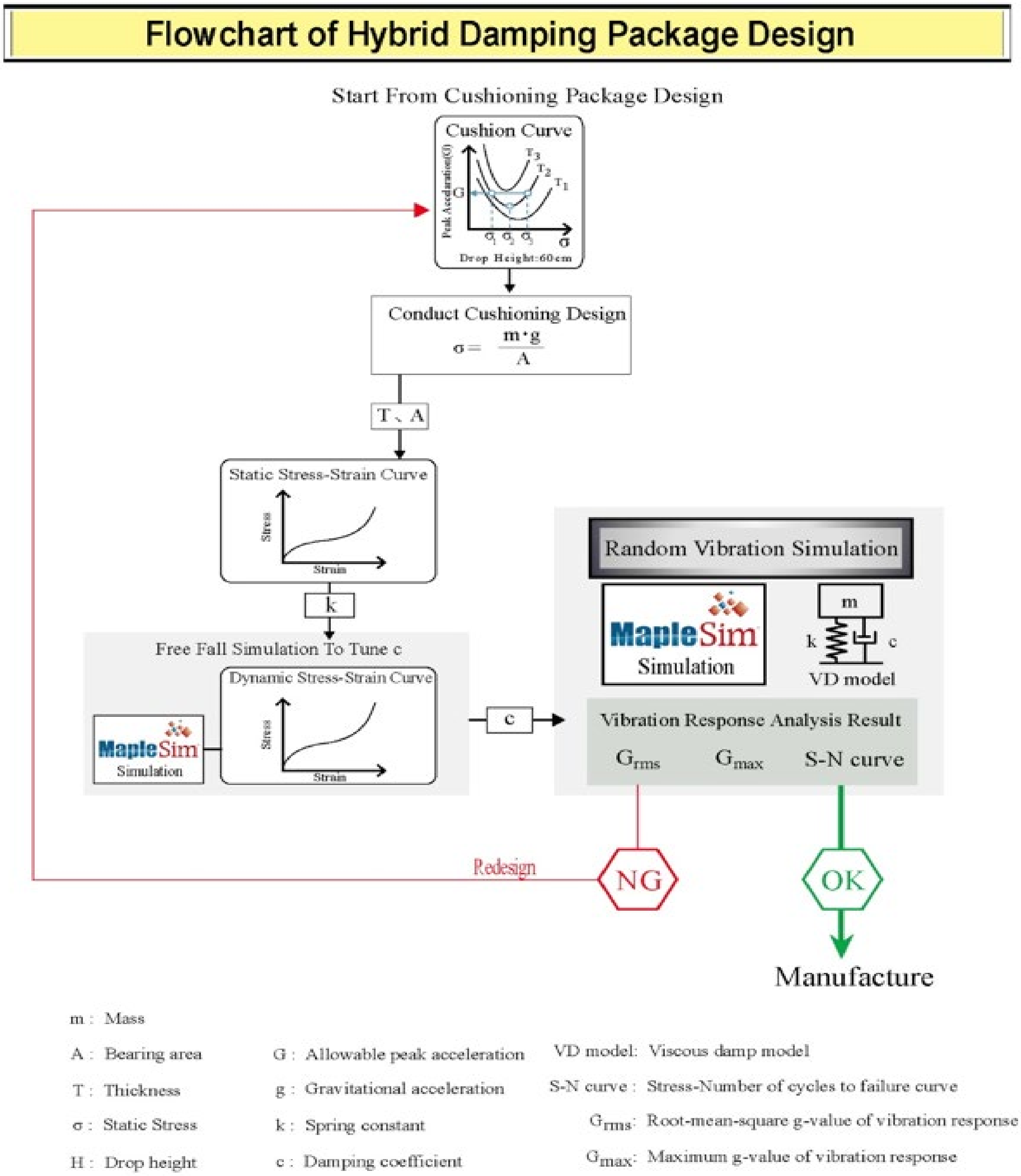

Fig.5. The flowchart of the Hybrid Damping Package Design process.

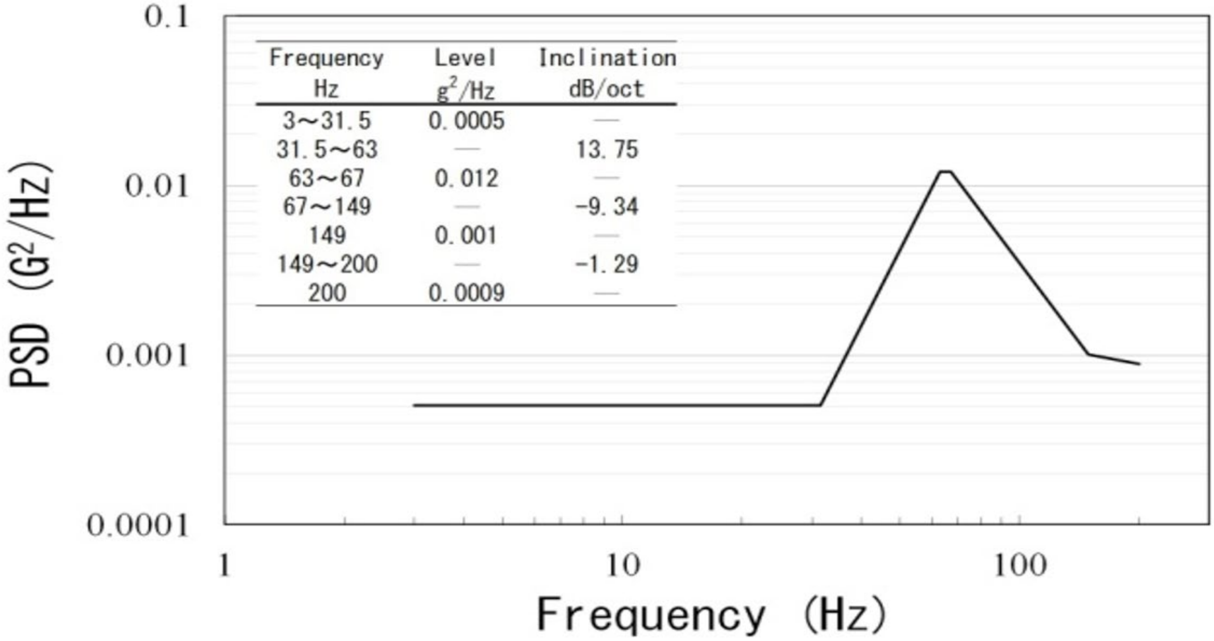

Fig.6: PSD of assumed transport environment

Fig.7: Dummy Product

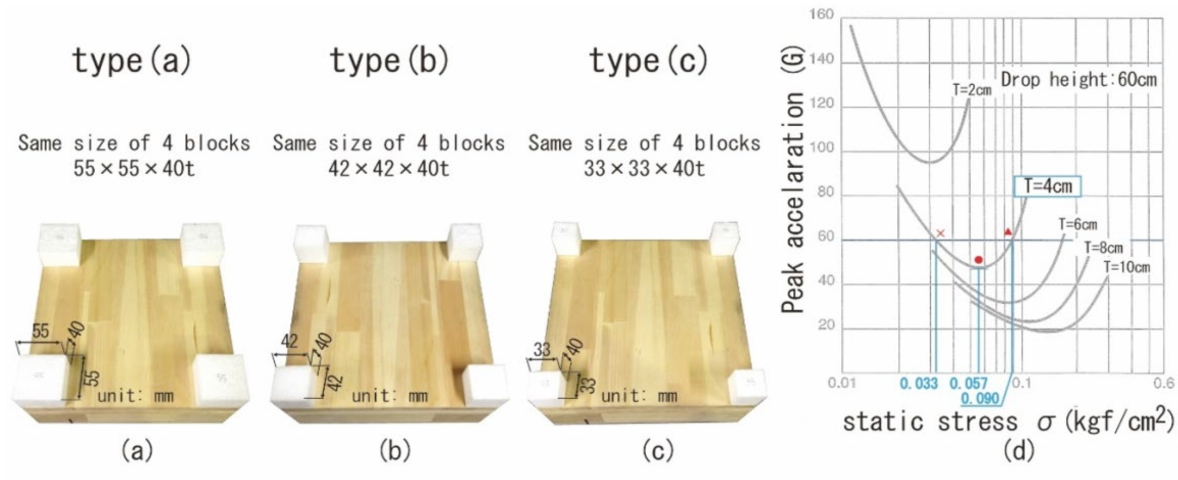

Fig.8 Cushion curve and dummies based on selected stresses.(a) σs=0.033 kgf/cm², (b) σs=0.057 kgf/cm², (c) σs=0.090 kgf/cm² and (d) cushion curve of Eperan™ XL38.

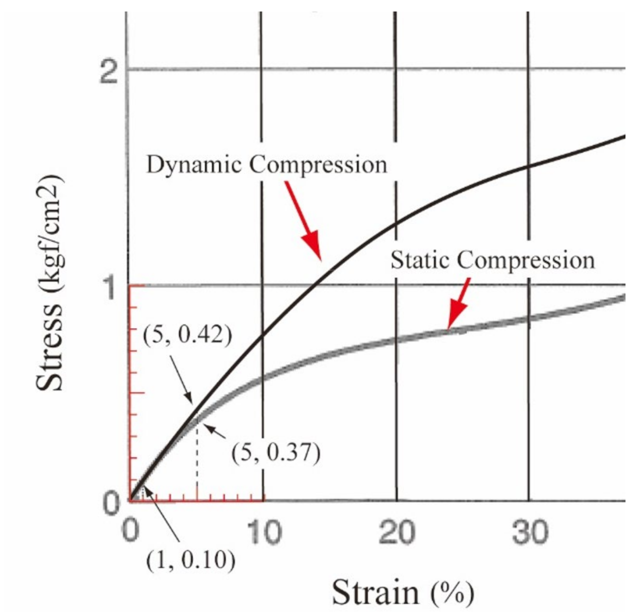

Fig.9. The Dynamic and Static Stress–Strain curve of Eperan^{TM} XL38.

4.1.3 Cushioning Package Design

Fig.8 (d) shows the cushion curve of the cushioning material according to the shock fragility (60G) for which the initial thickness is supposed to be 4 cm. Then, the range of bearing areas can be calculated as 121~44cm² from the static stress range (0.033~0.090 kgf/cm²). In the range of static stress, the minimum value is marked as × *(type (a)),* the maximum value as ▲ *(type (b)),* and the value corresponding to the minimum peak acceleration as ● *(type (c)).* In this study, the three static stresses are used to conduct cushioning package design to the bottom of package dummies (*Figs.8 (a), (b),* and *(c)*) and are discussed.

4.2 Calculation of Spring Constant and Damping Coefficient

To determine the optimal static stress with best anti-vibration performance in *type(a)*, *type(b)*, and *type(c),* vibration simulation was applied, in which the *k* and *c* of the VD model were needed. *Fig.9* shows the dynamic and static stress–strain curve of the cushioning material, which is usually provided by the material manufacturer. Although an obvious nonlinear stress–strain relationship is observed, when used in package vibration, a low range of strain (under 1%) is estimated because of the research efforts available about the measurements from and analysis of worldwide transport vibration data of truck, trailer, rail, and aircraft, which indicate that vibration acceleration levels are 0.1–0.4G[10-12]. In *Fig.9,* the strain of 1% is indicated

Table 1. *The k and c used in the simulation.*

	1% strain		5% strain	
	k(kN/m)	c(N·s/m)	k(kN/m)	c(N·s/m)
Type(a)	296.5	0	219.4	78
Type(b)	172.9	0	127.9	44
Type(c)	106.7	0	79.0	27

Table 2. The results of the actural vibration test and vibration simulation

	Grms of vibration simulation (G)		Grms of actual vibration test (G)
	1% strain	5% strain	
Type(a)	26.87	1.90	2.38
Type(b)	4.37	1.31	1.12
Type(c)	9.50	1.31	0.81

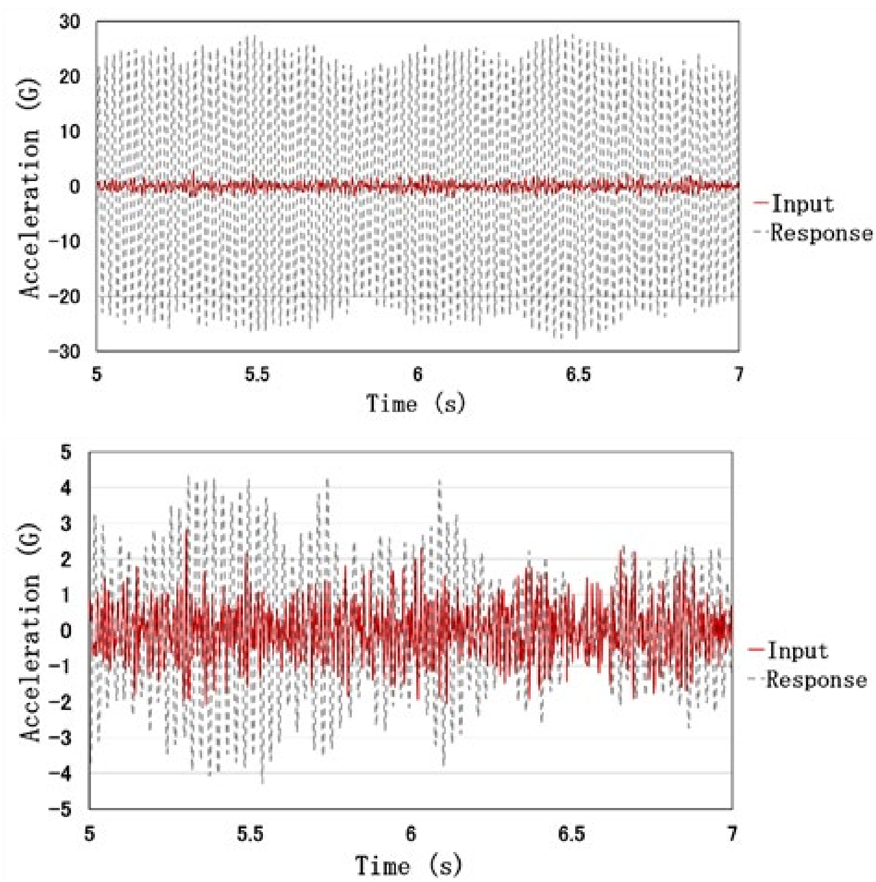

Fig.10 The vibration input and vibration response of type (a): (a) 1% Strain and (b) 5% Strain.

where the static compression graph and the dynamic compression graph overlap each other. According to the method of calculating the damping coefficient, which is illustrated in *Section 4.3*, c will be 0, which is obviously unrealistic and causes ridiculous vibration response. So, the point of 5% strain, where we can barely recognize the differences in the curves, is indicated as well from which the k can be calculated using the following formula.

$$k = \frac{\sigma \cdot A}{\varepsilon \cdot T} \tag{1}$$

Where k is the spring constant, σ is the stress, A is the bearing area, ε is the strain, and T is the thickness.

4.3 The Appropriate Method to Calculate Spring Constant and Damping Coefficient

We propose a method to obtain the c of a cushioning package system. *Fig.9* shows the Dynamic and Static stress–strain curve of Eperan™ XL38. First, when a cushioning package system is considered as a VD model, the curve obtained from static compression can be considered as $c = 0$ due to its obvious slow compression speed (10 mm/min); therefore, we used the same method in *4.2* to calculate k for the VD model at point (5, 0.37) and the results are shown in *Table 1.* Secondly, in order to obtain the c for the VD model, we used the Dynamic Compression curve of the same material. At the same strain of 5%, it showed stronger stress than the static one as (5, 0.42), and the difference was considered caused by the difference in the compression speed. The dynamic compression curve was plotted, based on JIS-Z0235, in which the drop height (H) is 0.6 m, so that the initial speed is determined to be approximately 3.46 m/s by using Equation (2). Then, we used Maplesim™ to establish a free-fall simulation using a VD model with the k calculated from the static compression curve and an initial speed of 3.46 m/s. When $c = 0$ (1% strain), the stress of the VD model was 0.37 kgf/cm², which is the value of the Static stress–strain curve. The c of the VD model is tuned until the stress changes from 0.37 to 0.42. The value that makes the stress of VD model 0.42 kgf/cm² is the proper c of the material. The results of types *(a), (b),* and *(c)* are shown in *Table 1,* and were used to conduct the vibration simulation.

$$v = \sqrt{2gH} \tag{2}$$

4.4 Vibration Simulation

Vibration simulation was conducted to predict the vibration response of the package dummies shown in *Figs.8 (a), (b),* and *(c).* The vibration input was obtained from the PSD in *Fig.6* using inverse Fourier transformation, which lasts for 30 s. *Fig.10 (a)* is the result of *type(a)* using the k and c of 1% strain, where $c = 0$. As mentioned in *Section 4.2,* the vibration response is extremely strong, caused by not considering the effect of attenuation. *Fig.10 (b)* shows the result using k and c of 5% strain. With the same methodology, the simulation was executed to the dummies shown in *Figs.8 (b)* and *(c)*, and the results are can be seen in *Table 2*. The results are the Grms value for the period of 5 to 30 s in order to avoid the influence of non-stationary vibration at the start. In *Table 2*, the results of actual random vibration tests *(Fig.11)* using the same PSD are shown as well.

4.5 The Optimal Static Stress for Cushioning and Anti-Vibration

As shown in *Table 2,* even though types *(a), (b),* and *(c)* are all suitable for cushioning packaging design, they produce different vibration responses. When choosing the optimal static stress, then we can make the following conclusions. *Type (a)* shows the worst vibration response and costs the most for material, so it obviously should not be applied. *Types (b)* and *(c)* are both under the assumed

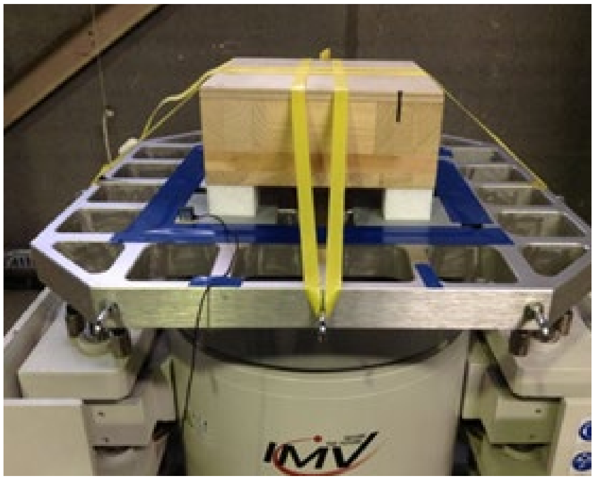

Fig.11 Vibration transmissibility test.

vibration fragility of Grms = 1.5G, so both of them are suitable to be applied. When there is a requirement to include a safe margin of cushioning performance, we will choose *type (b)*, because in the cushion curve, it has the lowest peak acceleration value. Conversely, when there is a requirement to reduce material costs, we will choose *type (c)*.

The discussion above shows that, with the help of vibration simulation, the vibration responses of various static stresses are predictable before conducting an actual vibration test. Thus, it is able to avoid the redesign caused by the failure in an actual vibration test, and package design will be more accurate and efficient.

5.0 CONCLUSION

By using Multibody Dynamics simulation as an aided tool for anti-vibration design, the optimal package that considers cushioning performance, anti-vibration performance, and the cost of materials can be determined before actually conducting a vibration test.

In the case study, we simply used the stress–strain curve of the cushioning material, which is usually provided by the manufacturer, to calculate the *k* and *c* of different static stresses. Therefore, the package designers do not need to do any tests to obtain the necessary parameters for executing the simulation, so the process allows them to find the optimal static stress very efficiently.

In this study, as the first step of applying Multibody Dynamics simulation to package design, a relatively simple model is used in the case study. However, the realistic situation is more complicated. In the next step, it is necessary to research more realistic package modeling to expand the use of the simulation.

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