Design and Random Vibration Simulation of the S-shaped Vibration Damping Structure for Transport Pallet

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Abstract. In order to improve the safety of containerized transport unit in palletized transport, this paper designs a new structural vibration damping pallet. Compared with the pallets that rely on material damping, the former is less affected by the environment, and can limit the horizontal and vertical deformation, making it elastic vertically to ensure the stability of cargo stacking. The relationship between its elastic deformation and material properties, size parameters and loads is obtained by establishing the mechanical model of the S-beam damping structure. Through finite element simulation of the static elastic deformation of the pallet, the relative error between the simulation and theoretical results is only about 1%, which verifies the theoretical basis of the vibration damping structure and reliability of the finite element modeling. In random vibration simulation, the S-shaped structural vibration damping pallet has a damping effect from 11.2Hz, and it reduces vibration energy of the traditional pallet by 46.3% and 9.3% less than the EPE material damping pallet and covers a wider damping frequencies. The results show that the pallet has obvious vibration reduction effect, can effectively protect the cargo and increase security of palletized transport.

1. Introduction
The pallet, known as one of the two key innovations in the logistics industry in the 20th century, is a unitized tool suitable for mechanized loading and unloading, transport and warehousing, and plays a key role in working through each link of logistics. In cargo transportation, wooden pallet accounts for about 87% in the pallet market, but its repair rate is as high as 68%[1]. This is mainly due to vibration and shock during transportation, which is also the main reason for cargo damage. Now in palletized transport, that is, the pallet-package-product is transported as a containerized unit, the long-distance complex transportation is a severe test for pallet. Most pallets on the market are rigid structures, focusing on load-bearing and turnover functions. If elasticity is added to the pallet to achieve the vibration reduction effect, there will be a further guarantee for the entire containerized unit.

Currently, many scholars at home and abroad have done extensive research on the properties of pallet materials and structures, but most of them focus on the load-bearing capacity and finite element analysis of the pallet in static state [2-3], as well as the optimization of the pallet structure design to make its load-bearing capacity stronger with the least materials [4], while there are very few designs for damping pallet. There are two main ways to reduce vibration of the pallet, one is to choose foamed plastic or rubber as the block material [5], which relies on the elastic damping characteristics of the material itself, called material damping, the other is to replace the original blocks with shock absorbers similar to the spring structure [6], which is given elasticity by structural design made of rigid materials, called structural vibration damping. Compared with structural vibration damping, material damping is...
more affected by the environmental, and cannot restrict the horizontal and longitudinal deformation, which may cause unstable stacking of cargo above. However, there are few choices of structural shock absorbers that can be used to transport pallets on the market, and the price is high, making it difficult to share and promote in palletized transport.

In order to make the pallet that was mainly used for storage turnover more suitable for the complex environment in long-distance transportation and to ensure the cargo safety, this paper designs the S-shaped structure of pallet blocks to reduce vibration, simulates its static elastic deformation and random vibration and compares the vibration damping effect with the traditional wooden pallet and the EPE material damping pallet. It is known that this simple and effective structure is easy to mass manufacture and promote so it will have a good application prospect.

2. Structural vibration damping design and mechanical model of the pallet

2.1. Structural vibration damping design of pallet blocks

The commonly used single-sided four-way wooden pallet is selected for redesign, as shown in Figure 1(a). Top decks, stringer plates, blocks and bottom decks are important parts of wooden pallets. According to the size specified in GB/T 2934-2007[7], 1200mm x 1000mm is preferred to be used, the width and thickness of top decks, stringer plates and bottom decks are 100 mm and 20 mm, and the size of blocks is 90 mm x 90 mm x 90 mm. The vibration damping structure is an S-shaped beam with dovetail tenon structure inserted into the block, easy to be disassembled and replaced, as shown in Figure 1(b). The S-shaped beam is bent downward under force, and S-shaped elastic deformation occurs, as shown in Figure 1(c), until compacted and closed. Then, the compacted pallet will become a rigid platform for cargo loading like a traditional wooden pallet. The excitation of cargo transportation is mainly in the vertical direction. This structure can limit the horizontal and vertical deformation, making the pallet elastic vertically to reduce vibration and ensure the stability of cargo stacking.

2.2. Mechanical model

The vibration damping performance of the pallet is reflected by the deformation of the S-shaped beam, that is, the deflection of the beam. Assume that a block bears the weight with a uniform mass of $m$. The upper wooden block is regarded as a rigid body, which can transmit the load to the BC section of the S-shaped beam, and the AD section is fixed to the lower wooden block, regarded as the fixed end. Then, the S-shaped beam can be simplified as an cantilever beam for analysis, as shown in Figure 2.

It can be seen from Figure 2 that the lengths of beam AD and beam BC are equal to $l_2$, and then the total length of the beam $l$ is $l_1 + 2l_2$. According to the theory of material mechanics[8], calculated that $F_B = q(l_1 + l_2)$, $M_B = \frac{l_1}{2} q (l_1 + l_2)^2$, $q = \frac{mg}{l_1 + 2l_2}$. The bending stiffness of the rectangular section
beam is \( EI = \frac{bh^2E}{l^2} \), and bending section coefficient is \( W_z = \frac{bh^3}{6} \). The deflection of the C-end of the beam is calculated by the superposition method, and after finishing:

\[
\omega_c = \frac{mg}{bh^2EI} \left( l_1^3 + \frac{3}{2} l_2^4 \right)
\]  
(1)

The maximum bending moment is at both ends of the beam AB:

\[
M_{\text{max}} = M_a - \frac{1}{2} ql_z^2
\]  
(2)

The maximum stress is:

\[
\sigma_{\text{max}} = \frac{M_{\text{max}}}{W_z} = \frac{3ql_z}{bh^2}
\]  
(3)

3. Finite element simulation analysis

3.1. Beam element finite element modeling

This pallet will show segmental variable stiffness. The first stage is the elastic stage: the S-shaped structure is not fully compacted. The stacking weight that can be carried at this stage is also the load range with vibration damping effect. When completely compacted, it enters the second stage, in which no damping effect, the rigidity is greatly increased, and it becomes a traditional wooden pallet so its maximum carrying capacity is the same as that of the wooden pallet. This paper focuses on the first stage with vibration damping effect.

The static compression process of the simplified beam is simulated in the finite element analysis software. The simplified beam element model is modeled according to the size parameters given below, \( l_1 = 41 \text{mm} \), \( l_2 = 24.5 \text{mm} \), \( l_3 = 2.5 \text{mm} \). The material is made of ABS thermoplastic material, which has high impact strength, high toughness and surface hardness in a relatively wide temperature range. It can adapt to severe transportation environments and its properties are shown in Table 1[9]. The path of the beam element is a line, so the automatic meshing method is adopted. It is set with the same force conditions and constraints as that in the theoretical analysis for the S-beam model. Suppose the block is compressed by 15kg, the uniform load of the beam is 1.634N/mm, the concentrated force at point B is 107.05N and concentrated couple is 3505.85 Nꞏmm.

| Table 1 Properties of the materials used in the pallet |
|-------------------------------------------------------|
| Density (kg·m⁻³) | Elastic modulus (MPa) | Poisson's ratio |
|--------|---------------------|----------------|
|        | \( E_x \) | \( E_y \) | \( E_z \) | \( \mu_{xy} \) | \( \mu_{xz} \) | \( \mu_{yz} \) |
| Pine   | 550   | 1103  | 16272 | 573  | 0.42  | 0.68  | 0.51  |
| ABS    | 1050  | 2000  |       |      | 0.4   |       |       |
| EPE    | 20    | 0.12  |       |      |       | 0.29  |       |

3.2. Finite element modeling of static compression of the block and the pallet

When analyzing the whole block and pallet, instead of the simplified beam element, solid element is used. The pallet materials except for the S-shaped structure are all made of pine, and its properties are shown in Table 1[10]. Set the contact type. The pallet structure is a whole, set to bonded contact. In order to prevent the cargo from jumping and causing secondary impact during transportation, the cargo will be tightly tied to the pallet, so the contact between them is set to bonded. The mesh is divided by Hex Dominant. The middle beam with a small thickness needs to be divided into multiple layers to be more accurate, usually at least two layers. Here is divided into five layers. Set loads and supports. Put 15kg of goods on the block and 135kg of goods on the pallet. A fixed support is set at the bottom.

In the EPE material damping pallet, the S-shaped structure is replaced with an EPE pad of the same height 14.9mm. Its material properties are shown in Table 1. The other settings remain unchanged.
3.3. Random vibration simulation

The random vibration excitation adopted is the acceleration PSD in ISTA-3E [11], as shown in Figure 3. This standard applies to unitized load transport with pallets.

Figure 3 The acceleration PSD in ISTA-3E

Modal analysis with preload is based on static analysis, and the input road spectrum frequency range is 1-200 Hz. Random vibration analysis is based on the modal analysis. Load the acceleration PSD in the vertical direction at the bottom of the pallet, and set the system damping coefficient to 0.2.

4. Results

4.1. The results of beam mechanics theory

According to the loads and sizes in the finite element simulation, the maximum deflection of the beam is 3.9187mm and the maximum stress is 32.164MPa calculated by formulas (1) and (3). The shear force diagram and bending moment diagram of the beam are shown in Figure 4. It can be seen that the maximum stress occurs at both ends of beam AB, which is the weakest part of this beam.

Figure 4 Shear force diagram and bending moment diagram

4.2. The static finite element simulation

The maximum vertical deformation is 3.9669mm. The maximum bending stress also occurs at both ends of the beam AB, as in the bending moment diagram, which is 32.164MPa shown in Figure 5. Compared with the theoretical results, the relative error of the maximum deformation is 1.2%.

The finite element results of the block solid element are shown in Figure 6. The phenomenon of stress singularity occurs, which means that the maximum stress will keep increasing with the finer mesh and the deformation will not change. It mostly appears at sharp corners. The reason for the divergence of stress results is not the error of the model itself, but the finite element model is based on the elastic theory where the stress at the sharp corner is infinite [12]. The stress at the stress singularity is invalid. If it cannot be ignored, you can refer to the nearby stress range corresponding to the same grid color that can cover three layers, which is more accurate. As shown in Figure 6(c), after the grid size is partly refined to 0.2mm, the light green grid can cover three layers so the stress at 0.6mm of the third layer is taken as a more accurate value. The stress at 0.6mm is 32.508MPa shown in Figure 6(d).

The finite element results of the pallet are shown in Figure 7, and the relative error with the beam theory is only 0.9%. Table 2 is the comparison between the finite element results and the theoretical results. The relative errors are all around 1%, which mutually verified the theoretical basis and the reliability of finite element simulation of the vibration damping structure.
Figure 5 The maximum deformation and bending stress of the beam element

(a) (b) (c) (d)

Figure 6 The maximum deformation and stress of the block solid element

Figure 7 The maximum deformation and stress of the pallet solid element

Table 2 The finite element analysis results and the theoretical results

|                         | Maximum stress at 0.6mm (MPa) | Maximum deflection (mm) | Relative error of maximum stress | Relative error of maximum deflection |
|-------------------------|-------------------------------|--------------------------|----------------------------------|-------------------------------------|
| Theoretical value       | 32.164                        | 3.9187                   | /                                | /                                   |
| Beam element            | 32.164                        | 3.9669                   | 0                                | 1.2%                                |
| Block                   | 32.508                        | 3.9354                   | 1.1%                             | 0.4%                                |
| Pallet                  | 32.466                        | 3.8843                   | 0.9%                             | 0.9%                                |

4.3. The random vibration simulation

In the modal analysis, the natural frequencies of the vibration damping pallet with a load of 135kg in 1-200Hz are shown in Table 3. Among them, the third natural frequency will cause the cargo to vibrate vertically upwards and resonate. The damping effect takes effect after this resonance frequency.

Table 3 Natural frequency of loaded vibration damping pallet

| Mode | 1  | 2  | 3  | 4  | 5  | 6  |
|------|----|----|----|----|----|----|
| Frequency (Hz) | 4.339 | 5.117 | 7.971 | 83.520 | 93.637 | 142.410 |

Figure 8 The acceleration PSD in random simulation

The 3σ equivalent stress and deformation of the vibration damping pallet in random vibration are 27.551MPa and 3.3442mm. The PSD vibration response of traditional wooden pallet, EPE material damping pallet and S-shaped structural vibration damping pallet in random vibration in ISTA-3E are
shown in figure 8, and their $G_{rms}$ representing the vibration energy are 0.54G, 0.34G and 0.29G, respectively. There is almost no difference between the output response and input excitation of the traditional wooden pallet, indicating that there is no damping effect. The acceleration PSD response of the EPE material damping pallet is lower than that of the traditional wooden pallet at 17.5Hz. The S-shaped structural vibration damping pallet resonates at the low peak, and starts reducing vibration at 11.2Hz before the second peak. Both of them avoid the fundamental frequency of vehicle transportation 2-5Hz. The vibration energy of road transportation is most concentrated in 0-50Hz [13], in which the effective damping frequency of EPE material damping pallet accounts for 65%, while the S-shaped structural vibration damping pallet accounts for 77.6%. It covers a wider range of damping frequencies. Compared with the traditional wooden pallet, the vibration energy of the S-shaped structural vibration damping pallet is reduced by 46.3%, and 9.3% less than that of the EPE material damping pallet.

5. Conclusion

This paper designs an S-shaped vibration damping structure for traditional wooden pallets and analyzes its damping effect in random vibration. The main conclusions are as follows:

1) Structural vibration damping for pallet is more suitable in palletized transport with complex environments than material damping. Moreover, this structure can limit the horizontal and vertical deformation, so that the pallet is only elastically deformed in the vertical direction to reduce vibration and ensure the stability of cargo stacking.

2) The vibration damping performance of this pallet is reflected by the elastic deformation of the S-shaped structure. The relationship between the elastic deformation and the material properties, size parameters and loads is obtained by establishing the mechanical theory model of the S-shaped beam, and then these parameters can be changed to customize the corresponding damping structure.

3) In random vibration simulation, compared with the traditional wooden pallet, the S-shaped structural vibration damping pallet has obvious vibration reduction effect, and covers a wider damping frequency than the EPE material damping pallet, and even makes more vibration energy reduced. It can effectively protect the cargo, and increase security of palletized transport.

The protection of goods in transportation often depends on packaging, but packaging is a disposable consumable, and its recycling system is not perfect yet, while pallet can be recycled, so when pallet is added with a vibration damping function, the protection of cargo will be sustainable. It provides a new idea for transportation package protection system.

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