

微波炉产品的隔振缓冲性能研究

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摘要: **目的** 降低微波炉及其内部元件因运输过程中的振动冲击而受到损坏或发生故障的可能性。**方法** 分析微波炉产品的结构特征, 研究微波炉产品包装系统的隔振缓冲性能, 建立六自由度包装系统(包括沿着 x , y , z 等 3 个方向的平动以及绕着 x , y , z 等 3 个方向的转动)的隔振缓冲力学模型及动力学方程。**结果** 采用计算机数值模拟的方法对隔振系统的振动响应进行模拟计算, 得到加速度峰值为 1.1131 m/s^2 ; 在理论建模的基础上, 制作了微波炉包装系统的实验装置, 通过振动实验得出实际加速度峰值为 1.2901 m/s^2 , 与计算机模拟结果的误差为 11.08%, 误差在工程允许范围内。**结论** 提出的包装系统隔振缓冲设计和评价方法理论可靠, 能为微波炉产品的隔振缓冲包装设计提供理论依据和有效参考。

关键词: 六自由度; 隔振缓冲; 运输包装; 微波炉

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Vibration Isolation-buffer Performance of Microwave Oven Products

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ABSTRACT: The work aims to reduce the possibility of damage or failure for the internal components in the microwave oven during transportation due to vibration. The structural characteristics of microwave oven products were analyzed. The vibration isolation-buffer performance of microwave oven product's packaging system was studied. The mechanical model for the vibration isolation-buffer performance of packaging system with six degrees of freedom (including the horizontal motion along x , y and z and the rotation around x , y and z) and the dynamic equation were established. The vibration response of the vibration isolation-buffer system was simulated by computer numerical simulation, and the acceleration peak value obtained was 1.1131 m/s^2 . Based on the theoretical modeling, the experimental device of the microwave oven product's packaging system was made. The actual acceleration peak value obtained from the vibration experiment was 1.2901 m/s^2 . The error was 11.08% compared with the result of computer simulation, which was within the allowable error range of the project. The proposed vibration isolation-buffer design and evaluation method for packaging system is theoretically reliable, which can provide theoretical basis and effective reference for the design of vibration isolation-buffer design of microwave oven products.

KEY WORDS: six degrees of freedom; vibration isolation-buffer; transport packaging; microwave oven

在运输过程中, 振动冲击是最为常见的外界激励^[1-3], 而衡量振动冲击强弱的主要采用振动加速度。美国明德林 (Mindlin R.D.)^[4]早在 1945 年就论述了包装物品在跌落过程中的运动规律, 主要讨论了

单自由度物品包装的动力响应。王志伟等^[5]讨论了单自由度正切非线性包装系统的冲击响应, 得出了阻尼系数比和冲击加速度峰值对系统冲击谱及破损边界曲线的影响规律; 姜久红和王军^[6-7]分别研究了具有

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易损件的两自由度正切非线性包装系统的参数对冲击谱和破损边界曲面的影响。以上的研究仅仅基于单自由度或二自由度系统的振动冲击情况,但是在实际包装运输过程中,常常以多自由度的形式出现。如果以最大为两自由度理论模型进行分析,必然会与实际情况产生较大的误差,得不到精确的隔振缓冲设计结果。由此,基于多自由度理论的包装设计理论^[8-14]应运而生。高德等进行了具有六自由度转动包装系统的正切非线性模型冲击响应方面的研究,得到了角加速度脉冲冲击下包装系统的响应规律^[15],但相关研究没有考虑弹簧和阻尼联合作用的情况。

文中拟建立具有24个(3×8)等效弹簧和阻尼的隔振缓冲系统模型和动力学方程,分别考虑在阻尼矩阵及在不计阻尼等情况下,推导出此6自由度隔振缓冲系统(即分别沿 x, y, z 等3个方向的平动,以及绕着 x, y, z 等3个轴的转动)施加沿轴向基础激励时的运动方程。另外,在理论研究的基础上,通过实验检验运动微分方程数值解的可靠性和误差范围,为多自由度隔振缓冲包装设计提供参考。

1 隔振缓冲模型的建立

1.1 包装结构模型

微波炉在运输的过程中,因道路颠簸等原因会受到振动冲击的影响,产生沿着 x, y, z 等3个方向的平动以及绕着 x, y, z 等3个方向的转动,因此一般会采用在四角安装泡沫缓冲垫等减振材料,使微波炉在各个方向都得到缓冲,其简化包装结构见图1。

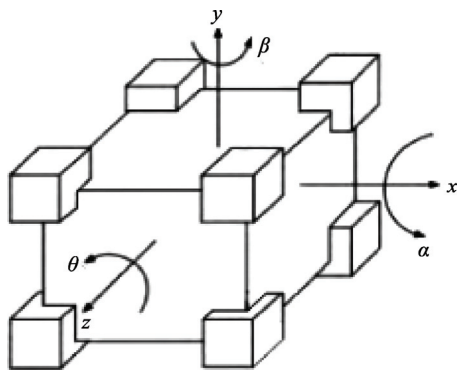


图1 包装结构
Fig.1 Package structure

坐标系的原点建在微波炉的质心位置,质心沿坐标轴方向的位移分别为 x, y, z ,绕坐标轴的转角分别为 α, β, θ ,此微波炉包装系统在空间中共有6个自由度。

1.2 包装动力学模型

一般的,系统的振动微分方程用矩阵形式表示为:

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{Q\} \quad (1)$$

式中: $[M]$ 为质量矩阵; $[C]$ 为阻尼矩阵; $[K]$ 为刚度矩阵; $\{Q\}$ 为广义力列阵; $\{X\}$ 为广义位移向量。在多自由度振动系统中,可运用拉格朗日方程来建立多自由度系统的运动方程。为了便于分析,将微波炉8个角上缓冲垫的等效刚度和阻尼分解到 x, y, z 等3个方向,分解后的动力学模型见图2,重心分布尺寸见图3。

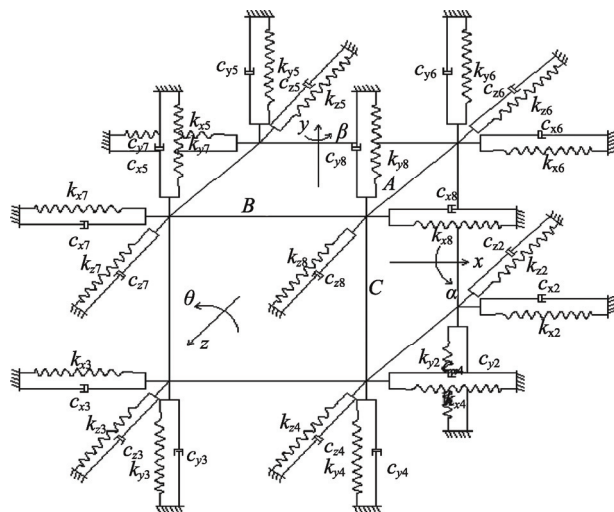


图2 分解后的动力学模型
Fig.2 Dynamic model after decomposition

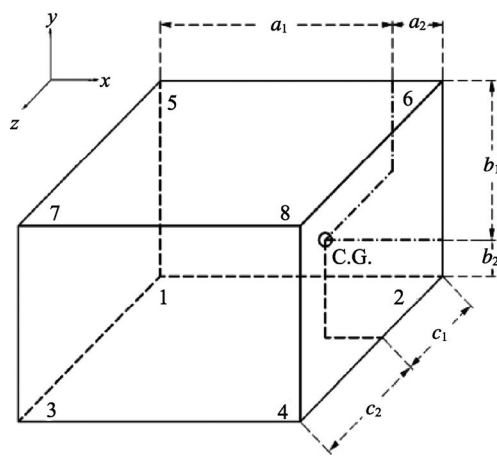


图3 标明尺寸的简化模型
Fig.3 A simplified model indicated with size

在图3中,微波炉包装的重心以C.G.表示,并以此为“O”点建立坐标系,8个角点的数字符号见图3。 k_{xi}, k_{yi}, k_{zi} 分别为第 i 点在 x, y, z 等3个方向的刚度系数, c_{xi}, c_{yi}, c_{zi} 分别为缓冲材料于第 i 点在 x, y, z 等3个方向的阻尼系数, α, β, θ 分别为物体绕 x, y, z 坐标轴的转角度,其正负号服从右手定则,则被微波炉包装件动能和势能之和的总能量为:

$$E = T + V =$$

$$\begin{aligned} & \frac{1}{2}m(\dot{x}^2 + \dot{y}^2 + \dot{z}^2) + \frac{1}{2}J_x\dot{\alpha}^2 + \frac{1}{2}J_y\dot{\beta}^2 + \frac{1}{2}J_z\dot{\theta}^2 + \\ & \frac{1}{2}k_{x1}(x - c_1\beta + b_2\theta)^2 + \frac{1}{2}k_{x2}(x - c_1\beta + b_2\theta)^2 + \\ & \frac{1}{2}k_{x3}(x + c_2\beta + b_2\theta)^2 + \frac{1}{2}k_{x4}(x + c_2\beta + b_2\theta)^2 + \\ & \frac{1}{2}k_{x5}(x - c_1\beta - b_1\theta)^2 + \frac{1}{2}k_{x6}(x - c_1\beta - b_1\theta)^2 + \\ & \frac{1}{2}k_{x7}(x + c_2\beta - b_1\theta)^2 + \frac{1}{2}k_{x8}(x + c_2\beta - b_1\theta)^2 + \\ & \frac{1}{2}k_{y1}(y + c_1\alpha - a_1\theta)^2 + \frac{1}{2}k_{y2}(y + c_1\alpha + a_2\theta)^2 + \\ & \frac{1}{2}k_{y3}(y - c_2\alpha - a_1\theta)^2 + \frac{1}{2}k_{y4}(y - c_2\alpha + a_2\theta)^2 + \\ & \frac{1}{2}k_{y5}(y + c_1\alpha - a_1\theta)^2 + \frac{1}{2}k_{y6}(y + c_1\alpha + a_2\theta)^2 + \\ & \frac{1}{2}k_{y7}(y - c_2\alpha - a_1\theta)^2 + \frac{1}{2}k_{y8}(y - c_2\alpha + a_2\theta)^2 + \\ & \frac{1}{2}k_{z1}(z + a_1\beta - b_2\alpha)^2 + \frac{1}{2}k_{z2}(z - a_2\beta - b_2\alpha)^2 + \\ & \frac{1}{2}k_{z3}(z + a_1\beta - b_2\alpha)^2 + \frac{1}{2}k_{z4}(z - a_2\beta - b_2\alpha)^2 + \\ & \frac{1}{2}k_{z5}(z + a_1\beta + b_1\alpha)^2 + \frac{1}{2}k_{z6}(z - a_2\beta + b_1\alpha)^2 + \\ & \frac{1}{2}k_{z7}(z + a_1\beta + b_1\alpha)^2 + \frac{1}{2}k_{z8}(z - a_2\beta + b_1\alpha)^2 \end{aligned} \quad (2)$$

根据能量守恒定律:

$$\frac{d}{dt}E = 0 \quad (3)$$

则有:

$$\begin{aligned} E = m(\ddot{x}\ddot{x} + \ddot{y}\ddot{y} + \ddot{z}\ddot{z}) + J_x\ddot{\alpha}\ddot{\alpha} + J_y\ddot{\beta}\ddot{\beta} + J_z\ddot{\theta}\ddot{\theta} + \\ (k_{x1} + k_{x2} + k_{x3} + k_{x4} + k_{x5} + k_{x6} + k_{x7} + k_{x8})x\dot{x} + \\ [(k_{x1} + k_{x2} + k_{x5} + k_{x6})c_1^2 + (k_{x3} + k_{x4} + k_{x7} + \\ k_{x8})c_2^2]\beta\dot{\beta} + [(k_{x1} + k_{x2} + k_{x3} + k_{x4})b_2^2 + (k_{x5} + \\ k_{x6} + k_{x7} + k_{x8})b_1^2]\theta\dot{\theta} + [-(k_{x1} + k_{x2} + k_{x5} + \\ k_{x6})c_1 + (k_{x3} + k_{x4} + k_{x7} + k_{x8})c_2](\beta\dot{x} + \dot{\beta}x) + \\ [(k_{x1} + k_{x2} + k_{x3} + k_{x4})b_2 - (k_{x5} + k_{x6} + k_{x7} + \\ k_{x8})b_1](\theta\dot{x} + \dot{\theta}x) + [-(k_{x1} + k_{x2})c_1b_2 + (k_{x3} + \\ k_{x4})c_2b_2 + (k_{x5} + k_{x6})c_1b_1 - (k_{x7} + k_{x8})c_2b_1] \cdot \\ (\beta\dot{\theta} + \dot{\beta}\theta) + (k_{y1} + k_{y2} + k_{y3} + k_{y4} + k_{y5} + k_{y6} + \\ k_{y7} + k_{y8})y\dot{y} + [(k_{y1} + k_{y2} + k_{y5} + k_{y6})c_1^2 + \\ (k_{y3} + k_{y4} + k_{y7} + k_{y8})c_2^2]\alpha\dot{\alpha} + [(k_{y1} + k_{y3} + k_{y5} + \\ k_{y7})a_1^2 + (k_{y2} + k_{y4} + k_{y6} + k_{y8})a_2^2]\theta\dot{\theta} + [(k_{y1} + \\ k_{y2} + k_{y5} + k_{y6})c_1 - (k_{y3} + k_{y4} + k_{y7} + k_{y8})c_2] \cdot \\ (\alpha\dot{y} + \dot{\alpha}y) + [-(k_{y1} + k_{y3} + k_{y5} + k_{y7})a_1 + (k_{y2} + \\ k_{y4} + k_{y6} + k_{y8})a_2](\theta\dot{y} + \dot{\theta}y) + [(k_{y1} + k_{y5})c_1a_1 + \\ (k_{y2} + k_{y6})c_1a_2 + (k_{y3} + k_{y7})c_2a_1 + (k_{y4} + k_{y8})c_2a_2] \cdot \\ (\alpha\dot{\theta} + \dot{\alpha}\theta) + (k_{z1} + k_{z2} + k_{z3} + k_{z4} + k_{z5} + k_{z6} + \end{aligned}$$

$$\begin{aligned} & k_{z7} + k_{z8})z\dot{z} + [(k_{z1} + k_{z3} + k_{z5} + k_{z7})a_1^2 + (k_{z2} + \\ & k_{z4} + k_{z6} + k_{z8})a_2^2]\beta\dot{\beta} + [(k_{z1} + k_{z2} + k_{z3} + \\ & k_{z4})b_2^2 + (k_{z5} + k_{z6} + k_{z7} + k_{z8})b_1^2]\alpha\dot{\alpha} + [(k_{z1} + \\ & k_{z3} + k_{z5} + k_{z7})a_1 - (k_{z2} + k_{z4} + k_{z6} + k_{z8})a_2] \cdot \\ & (\beta\dot{z} + \dot{\beta}z) + [-(k_{z1} + k_{z2} + k_{z3} + k_{z4})b_2 + (k_{z5} + \\ & k_{z6} + k_{z7} + k_{z8})b_1](\alpha\dot{z} + \dot{\alpha}z) + [-(k_{z1} + \\ & k_{z3})a_1b_2 + (k_{z2} + k_{z4})a_2b_2 + (k_{z5} + k_{z7})a_1b_1 - \\ & (k_{z6} + k_{z8})a_2b_1](\beta\dot{\alpha} + \dot{\beta}\alpha) = 0 \end{aligned} \quad (4)$$

考虑系统的振动特性, 设 ω_i 为第 i 个振动频率, 其相应的振型为 $[E^{(i)}]$; ω_j 为第 j 个振动频率, 其相应的振型为 $[E^{(j)}]$ 。将 ω_i 和 ω_j 分别代入振型方程, 由特征方程有:

$$[K][E^{(i)}] = \omega_i^2 [M][E^{(i)}] \quad (5)$$

$$[K][E^{(j)}] = \omega_j^2 [M][E^{(j)}] \quad (6)$$

在式(5)两边左乘 $[E^{(j)}]^T$, 对式(6)两边左乘 $[E^{(i)}]^T$, 则有:

$$[E^{(j)}]^T [K][E^{(i)}] = \omega_i^2 [E^{(j)}]^T [M][E^{(i)}] \quad (7)$$

$$[E^{(i)}]^T [K][E^{(j)}] = \omega_j^2 [E^{(i)}]^T [M][E^{(j)}] \quad (8)$$

将式(8)转置, 得到:

$$[E^{(j)}]^T [K][E^{(i)}] = \omega_j^2 [E^{(j)}]^T [M][E^{(i)}] \quad (9)$$

将式(7)减去式(9):

$$(\omega_i^2 - \omega_j^2)[Y^{(j)}]^T [M][Y^{(i)}] = 0$$

当 $\omega_i \neq \omega_j$ 时

$$[Y^{(j)}]^T [M][Y^{(i)}] = 0$$

对于质量矩阵 $[M]$ 系统主振型具有正交性, 同理可证明对于刚度矩阵 $[K]$ 系统主振型具有正交性, 故而可将此振动系统方程解耦, 将式(4)分解为 6 个等式:

$$\begin{aligned} m\ddot{x}\ddot{x} + (k_{x1} + k_{x2} + k_{x3} + k_{x4} + k_{x5} + k_{x6} + \\ k_{x7} + k_{x8})x\dot{x} + [(k_{x1} + k_{x2} + k_{x3} + k_{x4})b_2 - \\ (k_{x5} + k_{x6} + k_{x7} + k_{x8})b_1]\theta\dot{x} + [-(k_{x1} + k_{x2} + \\ k_{x5} + k_{x6})c_1 + (k_{x3} + k_{x4} + k_{x7} + k_{x8})c_2]\beta\dot{x} = 0 \end{aligned} \quad (10)$$

$$\begin{aligned} m\ddot{y}\ddot{y} + (k_{y1} + k_{y2} + k_{y3} + k_{y4} + k_{y5} + k_{y6} + k_{y7} + \\ k_{y8})y\dot{y} + [-(k_{y1} + k_{y3} + k_{y5} + k_{y7})a_1 + (k_{y2} + \\ k_{y4} + k_{y6} + k_{y8})a_2]\theta\dot{y} + [(k_{y1} + k_{y2} + k_{y5} + \\ k_{y6})c_1 - (k_{y3} + k_{y4} + k_{y7} + k_{y8})c_2]\alpha\dot{y} = 0 \end{aligned} \quad (11)$$

$$\begin{aligned} m\ddot{z}\ddot{z} + (k_{z1} + k_{z2} + k_{z3} + k_{z4} + k_{z5} + k_{z6} + k_{z7} + \\ k_{z8})z\dot{z} + [(k_{z1} + k_{z3} + k_{z5} + k_{z7})a_1 - (k_{z2} + \\ k_{z4} + k_{z6} + k_{z8})a_2]\beta\dot{z} + [-(k_{z1} + k_{z2} + k_{z3} + \\ k_{z4})b_2 + (k_{z5} + k_{z6} + k_{z7} + k_{z8})b_1]\alpha\dot{z} = 0 \end{aligned} \quad (12)$$

$$\begin{aligned} J_x\ddot{\alpha}\ddot{\alpha} + [(k_{y1} + k_{y2} + k_{y5} + k_{y6})c_1^2 + (k_{y3} + k_{y4} + k_{y7} + \\ k_{y8})c_2^2]\alpha\dot{\alpha} + [(k_{y1} + k_{y2} + k_{y5} + k_{y6})c_1 - (k_{y3} + \\ k_{y4} + k_{y7} + k_{y8})c_2]\dot{\alpha}y + [(k_{y1} + k_{y5})c_1a_1 + (k_{y2} + \\ k_{y6})c_1a_2 + (k_{y3} + k_{y7})c_2a_1 + (k_{y4} + k_{y8})c_2a_2]\dot{\alpha}\theta + \\ [(k_{z1} + k_{z2} + k_{z3} + k_{z4})b_2^2 + (k_{z5} + k_{z6} + k_{z7} + \end{aligned}$$

$$k_{z8}b_1^2]\alpha\dot{\alpha} + [-(k_{z1}+k_{z2}+k_{z3}+k_{z4})b_2 + (k_{z5}+k_{z6}+k_{z7}+k_{z8})b_1]\dot{\alpha}z + [-(k_{z1}+k_{z3})a_1b_2 + (k_{z2}+k_{z4})a_2b_2 + (k_{z5}+k_{z7})a_1b_1 - (k_{z6}+k_{z8})a_2b_1]\beta\dot{\alpha} = 0 \quad (13)$$

$$J_y\ddot{\beta}\ddot{\theta} + [(k_{x1}+k_{x2}+k_{x5}+k_{x6})c_1^2 + (k_{x3}+k_{x4}+k_{x7}+k_{x8})c_2^2]\beta\dot{\beta} + [-(k_{x1}+k_{x2}+k_{x5}+k_{x6})c_1 + (k_{x3}+k_{x4}+k_{x7}+k_{x8})c_2]\dot{\beta}x + [-(k_{x1}+k_{x2})c_1b_2 + (k_{x3}+k_{x4})c_2b_2 + (k_{x5}+k_{x6})c_1b_1 - (k_{x7}+k_{x8})c_2b_1]\dot{\beta}\theta + [(k_{z1}+k_{z3}+k_{z5}+k_{z7})a_1^2 + (k_{z2}+k_{z4}+k_{z6}+k_{z8})a_2^2]\beta\dot{\beta} + [(k_{z1}+k_{z3}+k_{z5}+k_{z7})a_1 - (k_{z2}+k_{z4}+k_{z6}+k_{z8})a_2]\dot{\beta}z + [-(k_{z1}+k_{z3})a_1b_2 + (k_{z2}+k_{z4})a_2b_2 + (k_{z5}+k_{z7})a_1b_1 - (k_{z6}+k_{z8})a_2b_1]\beta\dot{\alpha} = 0 \quad (14)$$

$$J_z\ddot{\theta}\ddot{\theta} + [(k_{x1}+k_{x2}+k_{x3}+k_{x4})b_2^2 + (k_{x5}+k_{x6}+k_{x7}+k_{x8})b_1^2]\theta\dot{\theta} + [(k_{x1}+k_{x2}+k_{x3}+k_{x4})b_2 - (k_{x5}+k_{x6}+k_{x7}+k_{x8})b_1]\dot{\theta}x + [-(k_{x1}+k_{x2})c_1b_2 + (k_{x3}+k_{x4})c_2b_2 + (k_{x5}+k_{x6})c_1b_1 - (k_{x7}+k_{x8})c_2b_1]\beta\dot{\theta} + [(k_{y1}+k_{y3}+k_{y5}+k_{y7})a_1^2 + (k_{y2}+k_{y4}+k_{y6}+k_{y8})a_2^2]\theta\dot{\theta} + [-(k_{y1}+k_{y3}+k_{y5}+k_{y7})a_1 + (k_{y2}+k_{y4}+k_{y6}+k_{y8})a_2]\dot{\theta}y + [(k_{y1}+k_{y5})c_1a_1 + (k_{y2}+k_{y6})c_1a_2 + (k_{y3}+k_{y7})c_2a_1 + (k_{y4}+k_{y8})c_2a_2]\alpha\dot{\theta} = 0 \quad (15)$$

一般情况下,包装的上部4个泡沫缓冲垫和下部的4个泡沫缓冲垫都是分别相同的,则有:

$$k_{x1}=k_{x2}=k_{x3}=k_{x4}=k_x$$

$$k_{x5}=k_{x6}=k_{x7}=k_{x8}=k'_x$$

$$k_{y1}=k_{y2}=k_{y3}=k_{y4}=k_y$$

$$k_{y5}=k_{y6}=k_{y7}=k_{y8}=k'_y$$

$$k_{z1}=k_{z2}=k_{z3}=k_{z4}=k_z$$

$$k_{z5}=k_{z6}=k_{z7}=k_{z8}=k'_z$$

于是,式(5—10)可简化为:

$$m\ddot{x} + (4k_x + 4k'_x)x + (4k_xb_2 - 4k'_xb_1)\theta + [(2k_x + 2k'_x)(c_2 - c_1)]\beta = 0 \quad (16)$$

$$m\ddot{y} + (4k_y + 4k'_y)y + (2k_y + 2k'_y)(a_2 - a_1)\theta + (2k_y + 2k'_y)(c_1 - c_2)\alpha = 0 \quad (17)$$

$$m\ddot{z} + (4k_z + 4k'_z)z + (2k_z + 2k'_z)(a_1 - a_2)\beta + (-4k_zb_2 + 4k'_zb_1)\alpha = 0 \quad (18)$$

$$J_x\ddot{\alpha} + [(2k_y + 2k'_y)(c_1^2 + c_2^2) + (4k_zb_2^2 + 4k'_zb_1^2)]\alpha + (2k_y + 2k'_y)(c_1 - c_2)y + (k_y + k'_y)(c_1a_1 + c_1a_2 + c_2a_1 + c_2a_2)\theta + (-4k_zb_2^2 + 4k'_zb_1^2)z + [2k_z(a_2b_2 - a_1b_2) + 2k'_z(a_1b_1 - a_2b_1)]\beta = 0 \quad (19)$$

$$J_y\ddot{\beta} + [(2k_x + 2k'_x)(c_1^2 + c_2^2) + (2k_z + 2k'_z)(a_2^2 + a_1^2)]\beta + (2k_x + 2k'_x)(c_2 - c_1)x + [2k_x(c_2b_2 - c_1b_2) + 2k'_x(c_1b_1 - c_2b_1)]\theta + (2k_z + 2k'_z)(a_1 - a_2)z + [2k_z(a_2b_2 - a_1b_2) + 2k'_z(a_1b_1 - a_2b_1)]\alpha = 0 \quad (20)$$

$$J_z\ddot{\theta} + [(4k_xb_2^2 + 4k'_xb_1^2) + (2k_y + 2k'_y)(a_1^2 + a_2^2)]\theta + (4k_xb_2 + 4k'_xb_1)x + [2k_x(c_2b_2 - c_1b_2) + 2k'_x(c_1b_1 - c_2b_1)]\beta + (2k_y + 2k'_y)(a_2 - a_1)y + (k_y + k'_y)(c_1a_1 + c_1a_2 + c_2a_1 + c_2a_2)\alpha = 0 \quad (21)$$

2 计算机模拟计算

以 y 轴方向振动为例,将实测质量 $m=7.9$ kg,上部泡沫衬垫刚度系数 $k_y=153.342\ 819$ N/m,下部泡沫衬垫刚度系数 $k'_y=66.493\ 333$ N/m,给定的初速度 $\dot{y}=0.002\ 58$ m/s,初始位移 $y=0.01$ m, $\alpha=0$, $\beta=0$, $\xi=0.85$ (其中 ξ 为系统的阻尼比,且 $\xi=\frac{C_n}{2\sqrt{k_n m}}$,阻

尼系数 $C_n=126.344143$ N·s/m,系统在 y 方向的刚度 $k_n=699.17404$ N/m,与上部泡沫衬垫刚度系数 k_y 不同)带入式(17)进行模拟求解,得到 y 方向的振动响应,加速度峰值为 1.1131 m/s²,见图4。

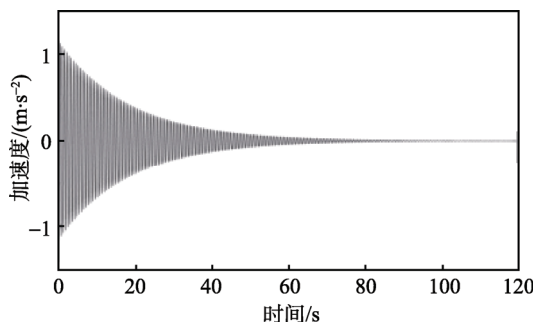


图4 y 方向的振动响应

Fig.4 Vibration response in the y direction

3 隔振缓冲实验

基于隔振系统的复杂性,对模型进行了简化,数值计算结果必然存在误差。为此,需要对其进行实验测试,验证模型是否能够满足隔振缓冲要求。由于所建立的动力学方程对于类似六自由度包装件具有普遍性,因此为了避免浪费,现将微波炉等效为铁块进行实验。

3.1 实验装置

实验装置见图5,角钢焊成的金属框架的每个角上用1根弹簧与铁块(10 cm×10 cm×10 cm)的8个角刚性连接,吊起铁块($m=7.9$ kg)。上面采用簧丝直径为1 mm、中径为10 mm的拉伸弹簧,弹性系数为238.56 N/m;下面采用簧丝直径为0.6 mm、中径为8 mm的弹簧,弹性系数为81.17 N/m。

传感器使用 INV9822A 型压电加速度传感器,将其安装在铁块上。振动信号的采集使用 Coinv DAPS

V10 软件系统, 用计算机进行数据分析处理。

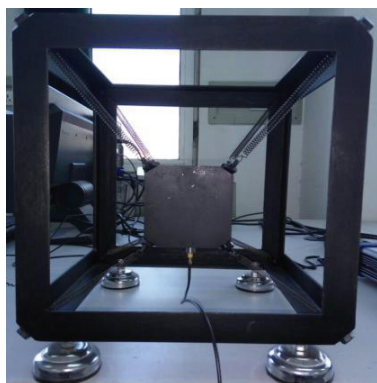


图5 隔振缓冲系统装置
Fig.5 Vibration isolation-buffer system

3.2 实验方法

将实验装置置于稳定的平台上, 给铁块施加沿 y 轴方向的 0.01 m 初始位移, 测量铁块的加速度响应。

3.3 实验结果及分析

测得的实验装置质量块的加速度响应见图6。

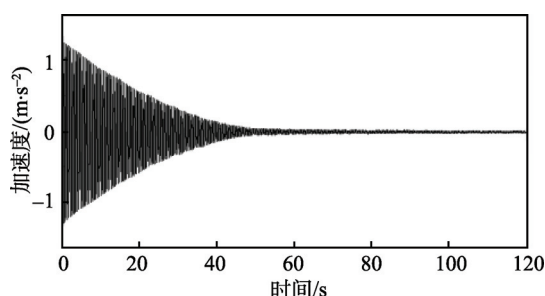


图6 测量的振动加速度响应
Fig.6 Measured vibration acceleration response

由图6可见, 实验测得的加速度峰值为 1.2901 m/s^2 , 与计算机模拟的加速度峰值 (1.1131 m/s^2) 相比, 两者的相对误差为 11.08% , 误差在工程允许范围内。进而比较图4和图6可知, 实验测试和计算机模拟的图形基本一致, 说明实验装置和力学模型两者是相似的, 初始条件也相同; 实验测试和模拟计算的固有频率十分相近, 表明实验装置的弹性系数与模拟计算采用的实际测试量是非常相近的; 通过实验测试和计算机模拟的曲线衰减率对比, 实验曲线的阻尼比为 0.83756 , 与实际测量的阻尼比 $\xi=0.85$ 相比, 相对误差为 1.46% 。实验说明, 隔振缓冲系统的微分方程和数值模拟计算在一定的条件下适用于包装件运输包装系统的动力学特性分析。

4 结语

在理论分析的基础上, 建立了微波炉隔振缓冲包

装系统的动力学模型和微分方程, 数值模拟了包装件的加速度响应, 得到了有阻尼系统的加速度响应曲线, 并与实验结果进行了对比, 其响应峰值和阻尼比的误差均小于 12% , 说明理论推导的隔振缓冲系统的动力学方程是合理的, 能为运输包装的隔振缓冲包装设计提供参考。

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