

轴向覆盖磁约束阻尼条对悬臂壳非轴对称振动的影响*

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摘要 应用 Rayleigh - Ritz 方法建立了局部磁约束阻尼壳的振动分析模型. 选取约束层的横向振动模式和面内振动模式作假设模态, 形成横向位移和面内位移. 调查了不同约束阻尼层配置下, 轴向覆盖磁约束阻尼条对悬臂壳非轴对称振动模态 ($m=1, n=1$) 损耗因子的影响. 研究表明: 当阻尼层远离该模态的节线 ($\theta = \pm \pi/2$), 磁约束阻尼处理的阻尼改进效果越明显. 阻尼层设置在 $\theta=0, \pi$ 处, 该模态的损耗因子最大, MCLD 处理的阻尼改进效果也最显著, 损耗因子提高约 40%. 可以通过改变阻尼层的长度及宽度可增加损耗因子, 但随二者的增加, 磁约束处理对阻尼的改进作用减小.

关键词 振动, 损耗因子, 磁体, 约束层, 壳

引言

为了提高薄壁等结构的减振效果, 大量的文献研究了各种主动、主动被动混合型约束层阻尼处理方法. 尽管这些主动振动控制方法已被证明比较有效, 但它们要求复杂的功放、控制系统. 而在振动与噪声控制中, 人们希望减振方法简便、可靠和经济. Ruzzene^[1] 首先提出了一种新型的被动磁约束阻尼 (MCLD) 减振方法, 该方法通过在梁约束层端部上设置永磁体, 使阻尼层获得比传统约束阻尼处理方法更高的剪应变, 从而增强粘弹层的阻尼耗能, 降低共振峰. Baz^[2] 实验证实了磁约束阻尼处理的减振效果. Ebrahim 研究了全覆盖磁约束板的一阶模态的减振效果^[3-4]. 本文作者分析了局部磁约束悬臂梁的减振机理及特性^[5]、磁约束对悬臂板的一阶扭转模态的减振效果^[6] 以及永磁体对全覆盖约束阻尼悬臂壳轴对称振动的影响^[7]. 在壳的振动中, 非轴对称模态一般起主要作用. 有时因为位置、费用等原因, 采用局部覆盖. 因此本文重点研究轴向覆盖磁约束阻尼条对悬臂壳非轴对称振动的影响.

1 分析模型

图 1 是为对称覆盖带状磁阻尼层的悬臂圆柱壳的示意图. 每一条阻尼层都从圆柱壳的固定端根

部铺设起, 当圆柱壳作振动时, 设置于支座和约束层上的永磁体间隙发生变化, 产生动态磁力, 从而增大了粘弹层的剪应变, 增加了系统耗能, 达到降低振动的目的. 图中的每一条阻尼层, 均作为各向同性薄壳处理, 阻尼层长度为阻尼层沿圆柱壳的轴向覆盖的长度 $L_0 = x_1 - x_0$. 阻尼层宽度为其沿圆柱壳圆周方向上覆盖的弧长 $b = r_c \times (\theta'_i - \theta'_0)$. θ'_0, θ'_i 为各条阻尼层圆周向上的起点、终点位置, x_0, x_1 为各条阻尼层在轴向上的起点、终点位置. 上标 j 代表第 j 条约束层.

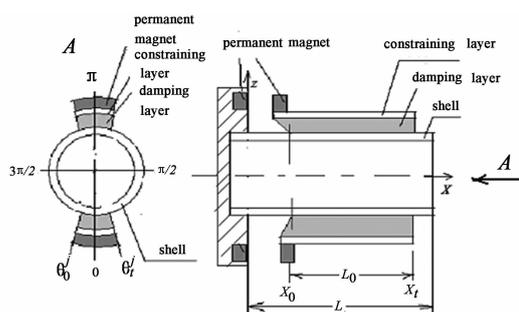


图 1 对称覆盖带状磁约束阻尼层的悬臂圆柱壳

Fig. 1 Cantilever cylindrical shell with symmetrically covered magnetic constrained layer damping strips

对于局部覆盖的阻尼壳, 由于其刚度和质量分布的不均匀, 求解其精确解相当困难, 故本文应用 Rayleigh - Ritz 方法来分析局部覆盖的磁约束阻尼悬臂壳的振动特性. 选取约束层的横向振动模态和

面内振动模态作假设模态,形成横向位移和面内位移,各层采用 Hoff 假设^[8]. 选取静平衡位置为振动零点,下文提到的纵向位移、作用力、剪应变等变量都是相对于静平衡位置来说的,由此基层及约束层的应力—应变关系表示为:

$$\sigma_{xx}^i = \frac{E_i}{1 - \nu_i^2} (\varepsilon_{xx}^i + \nu_i \varepsilon_{yy}^i), \sigma_{\theta\theta}^i = \frac{E_i}{1 - \nu_i^2} (\varepsilon_{\theta\theta}^i + \nu_i \varepsilon_{xx}^i),$$

$$\sigma_{x\theta}^i = G_i \varepsilon_{x\theta}^i \quad (i = s, c) \quad (1)$$

阻尼层的剪应变与剪应力关系为:

$$\sigma_{xx}^v = G_v \varepsilon_{xx}^v, \sigma_{\theta z}^v = G_v \varepsilon_{\theta z}^v \quad (2)$$

这里 G_v 是粘弹层的剪切模量,它是一个复数. 其中 σ_{xx} 、 $\sigma_{\theta\theta}$ 和 $\sigma_{x\theta}$ 是面内应力, E 是弹性模量, ν 是泊松比, G 是剪切模量, 上标 s, c, v 分别表示基层 (shell)、约束层 (CL) 及粘弹层 (VEM).

对于薄壳, x, θ 方向上的位移与壳的厚度成线性关系,认为各层横向位移 u_z 相同. 则

$$\begin{aligned} \varepsilon_{xx}^i &= \frac{\partial u_x^i}{\partial x} - z \frac{\partial^2 u_z}{\partial x^2}, \varepsilon_{\theta\theta}^i = \frac{1}{r_i} \frac{\partial u_\theta^i}{\partial \theta} + \frac{u_z}{r_i} - \frac{z}{r_i^2} \frac{\partial^2 u_z}{\partial \theta^2} \\ \varepsilon_{x\theta}^i &= \frac{\partial u_\theta^i}{\partial x} + \frac{1}{r_i} \frac{\partial u_x^i}{\partial \theta} - 2 \frac{z}{r_i} \frac{\partial^2 u_z}{\partial x \partial \theta}, \quad (i = s, c) \\ \varepsilon_{xz}^v &= \beta_x^v + \frac{\partial u_z}{\partial x}, \varepsilon_{x\theta}^v = \frac{\partial u_\theta^v}{\partial x} + \frac{1}{r_i} \frac{\partial u_x^v}{\partial \theta} - 2 \frac{z}{r_i} \frac{\partial^2 u_z}{\partial x \partial \theta} \end{aligned} \quad (3)$$

式中 u_x^i, u_θ^i 和 u_z^i 为中面位移, β_x^i 和 β_θ^i 扭转角, r_i 是各层中面的半径.

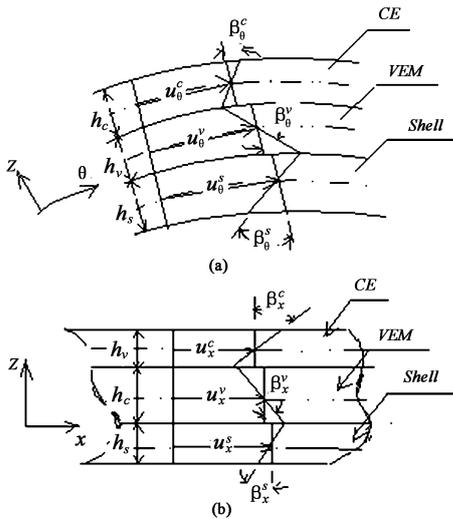


图 2 夹心部分变形 (a) θ 方向, (b) x 方向
Fig. 2 The deformation of sandwich section
(a) in the θ direction, (b) in the x direction

又由 Love 简化理论得到的 CL-VEM 及 VEM-

基层之间的关系如图 2, 则:

$$u_i^c(x, \theta) - \frac{h_c}{2} \beta_i^c(x, \theta) = u_i^v(x, \theta) + \frac{h_v}{2} \beta_i^v(x, \theta),$$

$$u_i^s(x, \theta) + \frac{h_s}{2} \beta_i^s(x, \theta) = u_i^s(x, \theta) + \frac{h_v}{2} \beta_i^v(x, \theta)$$

$$(i = x, \theta) \quad (4)$$

各层的变形能:

$$U_s = \frac{r_s}{2} \int_{-h_s/2}^{h_s/2} \int_0^L \int_0^{2\pi} \left[\frac{E_s}{1 - \nu_s^2} (\varepsilon_{xx}^s + \varepsilon_{\theta\theta}^s) + \frac{2E_s \nu_s}{1 - \nu_s^2} \varepsilon_{xx}^s \varepsilon_{\theta\theta}^s + G_s \varepsilon_{x\theta}^s \right] dx d\theta dz$$

$$U_v = \frac{r_v}{2} \int_{-h_s/2}^{h_s/2} \int_{x_0}^{x_1} \int_{\theta_0}^{\theta_1} (G_v \varepsilon_{xz}^v + G_v \varepsilon_{\theta z}^v) dx d\theta dz$$

$$U_c = \frac{r_c}{2} \int_{-h_s/2}^{h_s/2} \int_{x_0}^{x_1} \int_{\theta_0}^{\theta_1} \left[\frac{E_c}{1 - \nu_c^2} (\varepsilon_{xx}^c + \varepsilon_{\theta\theta}^c) + \frac{2E_c \nu_c}{1 - \nu_c^2} \varepsilon_{xx}^c \varepsilon_{\theta\theta}^c + G_c \varepsilon_{x\theta}^c \right] dx d\theta dz \quad (5)$$

由以上方程 (1-5) 可得用 u_x^i, u_θ^i 和 u_z^i 表示的势能为

$$\begin{aligned} U_s &= \frac{r_s}{2} \int_{-h_s/2}^{h_s/2} \int_0^L \int_0^{2\pi} \left[\frac{E_s}{1 - \nu_s^2} \left(\left(\frac{\partial u_x^s}{\partial x} \right)^2 + z^2 \left(\frac{\partial^2 u_z}{\partial x^2} \right)^2 \right) + \right. \\ &\quad \frac{E_s}{1 - \nu_s^2} \left(\frac{1}{r_s^2} \left(\frac{\partial u_\theta^s}{\partial \theta} \right)^2 + \frac{1}{r_s^2} u_z^2 + \frac{2}{r_s^2} \frac{\partial u_\theta^s}{\partial \theta} u_z + \right. \\ &\quad \left. \frac{z^2}{r_s^4} \left(\frac{\partial^2 u_z}{\partial \theta^2} \right)^2 \right) + \frac{2E_s \nu_s}{1 - \nu_s^2} \left(\frac{1}{r_s} \frac{\partial u_x^s}{\partial x} \frac{\partial u_\theta^s}{\partial \theta} + \frac{1}{r_s} \frac{\partial u_x^s}{\partial x} u_z + \right. \\ &\quad \left. \frac{z^2}{r_s^2} \frac{\partial^2 u_z}{\partial x^2} \frac{\partial^2 u_z}{\partial \theta^2} \right) + G_s \left(\frac{1}{r_s^2} \left(\frac{\partial u_x^s}{\partial \theta} \right)^2 + \left(\frac{\partial u_\theta^s}{\partial x} \right)^2 + \right. \\ &\quad \left. \frac{4z^2}{r_s^2} \left(\frac{\partial^2 u_z}{\partial x \partial \theta} \right)^2 + \frac{2}{r_s} \frac{\partial u_x^s}{\partial \theta} \frac{\partial u_\theta^s}{\partial x} \right] dx d\theta dz \end{aligned}$$

$$\begin{aligned} U_v &= \frac{r_v}{2} \int_{-h_s/2}^{h_s/2} \int_{x_0}^{x_1} \int_{\theta_0}^{\theta_1} \left[G_v \left(\frac{1}{h_v^2} u_x^c{}^2 + \frac{1}{h_v^2} u_x^s{}^2 + \frac{1}{4h_v^2} (h_c + \right. \right. \\ &\quad \left. \left. h_s + 2h_v) \left(\frac{\partial u_z}{\partial x} \right)^2 - \frac{2}{h_v^2} u_x^c u_x^s + \frac{1}{h_v^2} (h_c + h_s + \right. \right. \\ &\quad \left. \left. 2h_v) u_x^c \frac{\partial u_z}{\partial x} - \frac{1}{h_v^2} (h_c + h_s + 2h_v) u_x^s \frac{\partial u_z}{\partial x} \right) + \right. \\ &\quad \left. G_v \left(\left(\frac{1}{h_v} - \frac{1}{2r_v} \right)^2 u_\theta^c{}^2 + \left(\frac{1}{h_v} + \frac{1}{2r_v} \right) u_\theta^s{}^2 - 2 \left(\frac{1}{h_v} - \right. \right. \right. \\ &\quad \left. \left. \frac{1}{4r_v^2} \right) u_\theta^c u_\theta^s + \left(\frac{h_c}{2h_v r_c} + \frac{h_s}{2h_v r_s} - \frac{h_c}{4r_v r_c} + \frac{h_s}{4r_v r_s} + \right. \right. \\ &\quad \left. \left. \frac{1}{r_v} \right)^2 \left(\frac{\partial u_z}{\partial \theta} \right)^2 + 2 \left(\frac{1}{h_v} - \frac{1}{2r_v} \right) \left(\frac{h_c}{2h_v r_c} + \frac{h_s}{2h_v r_s} - \right. \right. \\ &\quad \left. \left. \frac{h_c}{4r_v r_c} + \frac{h_s}{4r_v r_s} + \frac{1}{r_v} \right) u_\theta^c \frac{\partial u_z}{\partial \theta} - 2 \left(\frac{1}{h_v} + \frac{1}{2r_v} \right) \left(\frac{h_c}{2h_v r_c} + \right. \right. \\ &\quad \left. \left. \frac{h_s}{2h_v r_s} - \frac{h_c}{4r_v r_c} + \frac{h_s}{4r_v r_s} + \frac{1}{r_v} \right) u_\theta^s \frac{\partial u_z}{\partial \theta} \right] dx d\theta dz \end{aligned}$$

$$\begin{aligned}
 U_c = & \frac{r_c}{2} \int_{-h_c/2}^{h_c/2} \int_0^L \int_{\theta_0}^{\theta_1} \left[\frac{E_c}{1-v_c^2} \left(\frac{\partial u_x^c}{\partial x} \right)^2 + z^2 \left(\frac{\partial^2 u_z^c}{\partial x^2} \right)^2 + \right. \\
 & \frac{E_c}{1-v_c^2} \left(\frac{1}{r_c^2} \left(\frac{\partial u_\theta^c}{\partial \theta} \right)^2 + \frac{1}{r_c^2} u_z^c + \frac{2}{r_c^2} \frac{\partial u_\theta^c}{\partial \theta} u_z^c + \right. \\
 & \frac{z^2}{r_c^4} \left(\frac{\partial^2 u_z^c}{\partial \theta^2} \right)^2 + \frac{2E_c v_c}{1-v_c^2} \left(\frac{1}{r_c} \frac{\partial u_x^c}{\partial x} \frac{\partial u_\theta^c}{\partial \theta} + \frac{1}{r_c} \frac{\partial u_x^c}{\partial x} u_z^c + \right. \\
 & \frac{z^2}{r_c^2} \frac{\partial^2 u_z^c}{\partial x^2} \frac{\partial^2 u_z^c}{\partial \theta^2} \left. \right) + G_c \left(\frac{1}{r_c^2} \left(\frac{\partial u_x^c}{\partial \theta} \right)^2 + \left(\frac{\partial u_\theta^c}{\partial x} \right)^2 + \right. \\
 & \left. \left. \frac{4z^2}{r_c^2} \left(\frac{\partial^2 u_z^c}{\partial x \partial \theta} \right)^2 + \frac{2}{r_c} \frac{\partial u_x^c}{\partial \theta} \frac{\partial u_\theta^c}{\partial x} \right) \right] dx d\theta dz \quad (6)
 \end{aligned}$$

只考虑动态磁力所做的功 $W_{mag}^{[5]}$

$$W_{mag} = \sum_{j=1}^2 \int_{\theta_0^j}^{\theta_1^j} \frac{1}{2} K_{mag}(x_1, \theta) (\Delta x)^2 d\theta \quad (7)$$

式中：

$$\begin{aligned}
 \Delta x(x_1, \theta) & \approx h_v \varepsilon_{xz}^v \Big|_{x=x_1, \theta=\theta}, \\
 K_{mag}(x, \theta) & = \left(\frac{\partial F_{mag}(x, \theta)}{\partial x} \right) \Big|_{x=x_0, \theta=\theta}
 \end{aligned}$$

各层的动能：

$$\begin{aligned}
 T_s & = \frac{1}{2} \rho_s h_s r_s \int_0^{2\pi} \int_0^L \dot{u}_z^2 dx d\theta \\
 T_v & = \frac{1}{2} \rho_v h_v r_v \int_{\theta_0}^{\theta_1} \int_{x_0}^{x_1} \dot{u}_z^2 dx d\theta \\
 T_c & = \frac{1}{2} \rho_c h_c r_c \int_{\theta_0}^{\theta_1} \int_{x_0}^{x_1} \dot{u}_z^2 dx d\theta \quad (8)
 \end{aligned}$$

一个振动周期内的能量函数为：

$$\phi = \int_0^{2\pi/\omega} (U - T - W_{mag}) dt \quad (9)$$

应用 Rayleigh-Ritz 方法建立了壳的近似振动分析模型. 选取分别满足约束层及壳的边界条件的容许函数形成横向位移和面内位移.

$$\begin{aligned}
 u_z(x, \theta, t) & = \sum_{m=1}^{\infty} \sum_{n=0}^{\infty} A_{mn} w_m(x) \cos(n\theta) e^{j\omega t} \\
 u_x^s(x, \theta, t) & = \sum_{m=1}^{\infty} \sum_{n=0}^{\infty} B_{mn}^s u_m^s \cos(n\theta) e^{j\omega t} \\
 u_\theta^s(x, \theta, t) & = \sum_{m=1}^{\infty} \sum_{n=0}^{\infty} C_{mn}^s w_m(x) \sin(n\theta) e^{j\omega t} \\
 u_x^c(x, \theta, t) & = \sum_{m=0n=0}^{\infty} B_{mn}^c \cos(m\pi(x-x_0)/L_0) \cos(n\theta) e^{j\omega t} \\
 u_\theta^c(x, \theta, t) & = \sum_{m=0n=0}^{\infty} C_{mn}^c w_m(x) \cos \frac{n\pi(\theta-\theta_0^j)}{(\theta_1^j-\theta_0^j)} e^{j\omega t} \quad (10)
 \end{aligned}$$

其中

$$\begin{aligned}
 w_m(x) & = \cosh(\lambda_m x) - \cos(\lambda_m x) - e_m [\sin(\lambda_m x) - \sin(\lambda_m x)] \quad m=1, 2, 3, \dots, \lambda_m = (m-0.5)\pi/L; \\
 e_m & = \frac{\sinh(\lambda_m L) - \sin(\lambda_m L)}{\cosh(\lambda_m L) + \cos(\lambda_m L)};
 \end{aligned}$$

当 $m=0$ 时，

$$\begin{aligned}
 w_m(x) & = 1 \\
 u_m^s & = \sinh(\lambda_m x) + \sin(\lambda_m x) - e_m [\cosh(\lambda_m x) - \cos(\lambda_m x)] \quad m=1, 2, 3, \dots
 \end{aligned}$$

因为约束层与基层壳的边界条件不同, 约束层边部在 x 和 θ 方向无约束, 故以上容许函数中在约束层面内位移中, m 是从 0 开始时, 目的是计及在约束层面内运动存在的刚体模态.

将假设的纵向和横向位移表达式代入能量函数中, 分别对未知系数 $A_{mn}, B_{mn}^{s,v}, C_{mn}^{s,v}$ 求导, 使能量函数最小, 得到关于 $B_{mn}^{s,v}, C_{mn}^{s,v}$ 的方程, 进一步消去 $B_{mn}^{s,v}, C_{mn}^{s,v}$, 从而得到由横向位移 A_{mn} 表示的壳的特征方程

$$(-[M]\omega^2 + [K]) \{A_{11}, A_{12}, \dots, A_{mn}\}^T = 0 \quad (11)$$

由特征方程进而可得到第 rk 阶的特征值 λ_{rk} , 并由 λ_{rk} 求得第 rk 阶的模态频率 f_{rk} 及第 rk 阶的模态损耗因子 η_{rk} .

2 讨论

选取分析参数为: $L=500\text{mm}, r_s=100\text{mm}, h_s=0.5\text{mm}, h_v=4\text{mm}, h_c=0.25\text{mm}, E_s=E_c=71\text{GPa}, \rho_v=150\text{Kg}/\text{m}^3, \rho_s=\rho_c=2700\text{Kg}/\text{m}^3; G_v=(1+0.4i)\times 10^5\text{MPa}$. 两条约束阻尼层长均为 $L_0=0.3L$, 覆盖弧长 $b=r_s \times \pi/6$. 分别铺设在位置 $1: x_0^1=0.4\text{mm}, \theta^1=0$ 及 $x_0^2=0.4\text{mm}, \theta^2=\pi, (\theta^j=(\theta_0^j+\theta_1^j)/2)$, 上标表示第 j 条阻尼层;), 相对壳的中心轴对称, 从圆柱壳的根部 x_0^j 开始铺设. 选用永磁体 NdFeB, 剩余磁感应强度 1.119T , 沿 x 方向的间隙为 0.40mm , 磁体覆盖弧长与约束阻尼层覆盖弧长相同, 径向高度为 7mm . 轴向尺寸为 7mm . 由等效电流法可得 $K_{mag}=1.016 \times 10^6 \text{N}/\text{m}^2$ ^[5]. 文献[7]研究了全覆盖磁约束阻尼处理对悬臂圆柱壳的轴对称振动的减振效果, 即相当于本文的 $m=1, n=0$ 模态. 实际中, 非轴对称振动更容易产生, 故本文重点研究局部磁约束阻尼处理对非轴对称振动的模态 ($m=1, n=1$) 损耗因子 η 的影响.

以下的分析参数, 如无说明, 则与上述相同.

1) 磁阻尼层覆盖位置对模态损耗因子的影响

先保持阻尼层的长度、覆盖弧长不变, 改变周向覆盖位置, 即其中一条的覆盖位置 θ 从 0 变化至 π , 另一条保持与其轴对称的关系. 得到损耗因子

与 θ 的关系如图 3. 从图可知, 当阻尼层远离该模式的节线 ($\theta = \pm \pi/2$), PCLD 的损耗因子增加, MCLD 处理的阻尼改进效果也越明显. 阻尼层设置在 $\theta = 0, \pi$ 处, PCLD 和 MCLD 在该模式的损耗因子最大; MCLD 处理的阻尼改进效果也最显著, 损耗因子提高约 40%. 其原因在于: 磁力主要在轴向与与约束阻尼结构产生相互作用. 位于节线处附近, 粘弹层的 xz 方向剪应变小, 动态磁力对约束层 xz 的方向应变影响小, 不利于提高减振效果; 而阻尼层远离该模式的节线, 情形正相反. 图示结果表明, 两条阻尼层对称覆盖在 $\theta = 0$ 及 $\theta = \pi$ 处, 有利于减少 $m = 1, n = 1$ 模式的振动.

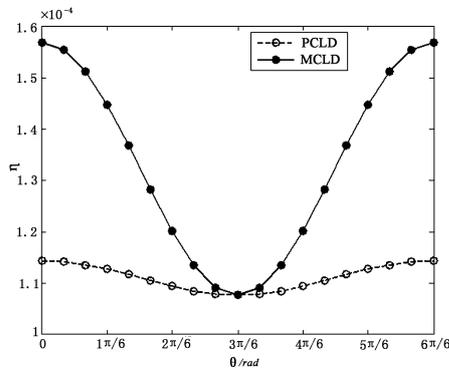


图3 θ 与 η 的关系
Fig.3 Variation of η with θ

2) 磁阻尼层的长度的影响

保持阻尼层的覆盖弧长 ($b = r_s \times \pi/6$) 不变, 将两条阻尼层对称覆盖在 $\theta = 0$ 及 $\theta = \pi$ 处, 然后改变阻尼层的长度, 每条阻尼层的长度由 $L_0 = 0.3L$ 到 $L_0 = L$. 得到损耗因子与 L_0 的关系如图 4.

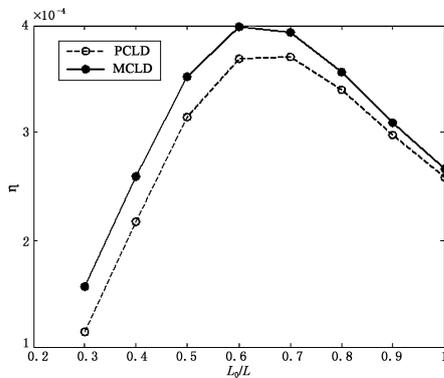


图4 长度 L_0 与 η 的关系
Fig.4 Variation of η with L_0

从图 4 可知, 通过磁约束处理后, 模式的损耗因子都有了一定地提高, 但是, 阻尼层的长度越长,

损耗因子的相对改变量越小. 这主要由于阻尼层的总阻尼应包含 x 及 θ 两个方向上产生的阻尼值. 随着阻尼长度的增加, θ 方向剪应变引起的阻尼在总阻尼中的比重增加, 因此, 磁力引起的 xz 方向阻尼在总阻尼中的比重增加减少, 故损耗因子的相对改变量相应减小, 这与 MCLD 对梁的一阶模态阻尼改进效果有些不同^[3]. 图示结果也表明, 当阻尼层长度大于某一数值后, 损耗因子随着阻尼层长度的增大而减小, 这一点与梁类似.

3) 磁阻尼层覆盖角对模态损耗因子的影响

保持阻尼层的长度 ($L_0 = 0.3L$) 不变, 仍然将两条阻尼层对称覆盖在 $\theta = 0$ 及 $\theta = \pi$ 处, 改变阻尼层的覆盖角 $\Delta\theta$, 得到损耗因子与 $\Delta\theta$ 的关系如图 5, 由图 5 可知, 经过磁约束处理后, 损耗因子也得到了地提高, 但是, 随着 $\Delta\theta$ 的增加, 损耗因子的相对变化减小, 这是因为, $\Delta\theta$ 越大, 阻尼层越靠近节线 ($\pm \pi/2$), 动态磁力对约束层的应变影响越小.

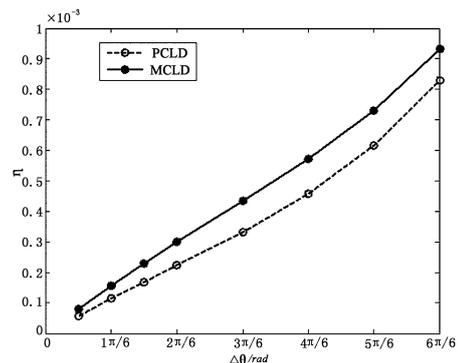


图5 覆盖角 $\Delta\theta$ 与 η 的关系
Fig.5 Variation of η with $\Delta\theta$

3 结论

本文对悬臂壳的非轴对称模态 ($m = 1, n = 1$) 采用磁约束阻尼处理的阻尼改进效果进行了研究. 得到如下结论:

- 1) 对于悬臂壳的非轴对称模态 ($m = 1, n = 1$), 磁约束阻尼层的铺设位置离节线 $\pm \pi/2$ 越远, 阻尼改进效果越好.
- 2) 可以通过改变阻尼层的长度及宽度来增加损耗因子, 但随二者的增加, 磁约束处理后损耗因子虽然增加, 但相对增加量随之减小.

结合磁约束处理对轴对称模态的改进效果^[4] 可知, 在适当的位置上设置 MCLD 可有效提高壳的阻尼, 降低振动.

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EFFECT OF AXIAL-COVERED MAGNETIC CONSTRAINED DAMPING STRIPS ON UNAXIAL-SYMMETRICAL VIBRATION OF A CANTILEVER CYLINDRICAL SHELL*

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Abstract The Rayleigh-Ritz method was applied for the damping analysis of flexural vibration of the cantilever cylindrical shell with partial magnetic constrained layer damping treatment (MCLD). The analysis was carried out in terms of resonant frequencies and the associated modal system loss factors. Single-term solutions for respective modes were assumed for the x-axial and circumference directions in-plane displacements of the constraining layer and the radial displacement of the shell. We obtained the improvement of damping characteristics for the unaxial-symmetrical vibration mode ($m = 1, n = 1$) using MCLD patches with different configurations. The obtained results indicated that the MCLD with patch far from the line $\theta = \pm \pi/2$ could enhance significantly the loss factors η . Provided that the damping layer is located at $\theta = 0, \pi$, both PCLD and MCLD can gain maximal modal loss factor, and MCLD can increase the loss factor about 40 per cents versus PCLD. Increasing damping layer length or circumference angle can cause η rise, but decrease the damping improvement effect of MCLD.

Key words vibration, loss factor, magnets, constraining layer, shell

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