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复杂边界条件弹性薄板非线性振动问题 的边界积分方程解法*

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[摘要] 本文根据 Von Karman 非线性板弯曲理论, 导出了薄板大挠度振动问题的积分方程表达式; 利用谐波平衡法, 并同时对方程积分项及区域积分项进行离散, 获得振幅相关的特征值方程; 提出了一种可行的迭代解法, 求解非线性自由振动的幅频关系。对多种组合边界条件的薄板进行了数值分析及比较, 结果相当满意。

关键词: 边界积分方程; 薄板; 非线性振动

一、引言

在航空航天等高科技领域, 板壳类结构的非线性振动问题一直为人们所关注。对于规则几何形状、较简单边界约束条件的板振动问题, 已有许多解析分析结果可供参考^[1], 而对于不规则形状及较复杂边界约束的情形, 解析分析方法则多有不便之处。迄今为止, 用数值方法分析板壳非线性自由振动、谐激励响应一类的周期解问题的研究工作并不多见。为数不多的一些有限元分析结果^[2~4], 由于引入了过多的简化而难以普遍适用于一般情况下的薄板振动问题。

边界积分方程法在工程结构分析中的应用领域日益拓广, 并逐步向非线性方向发展^[5,6]。本文从薄板非线性弯曲的 Von Karman 理论出发, 以线弹性静力问题的基本解建立积分方程表达式, 使用边界及区域离散相结合的方法, 再由谐波平衡法, 导出振幅相关的特征值方程。在边界上, 直接以弯曲及中面变形对应的各广义位移和广义力为基本参数, 可以方便、灵活地实施各种边界约束条件; 在域内, 仅需对挠度场本身进行插值离散, 避免了有限元方法的 C^1 类连续问题。提出了一种有效的迭代求解方案, 并对多种边界组合情况进行了数值分析与比较。

二、基本关系及边界积分方程式

如图 1 所示, 薄板大挠度弯曲振动的微分方程为

$$D \nabla^4 W = f + N_{ij} W_{,ij} - \rho W \quad (1)$$

$$N_{ij,j} = \rho u_i \quad (2)$$

其中

$$\varepsilon_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i} + W_{,i} W_{,j}) \quad (3)$$

* 本文工作得到国家自然科学基金资助

$$N_{ij} = h E_{ijkl} e_{kl}$$

(4)

各张量指标满足求和约定, $i, j, k, l \in \{1, 2\}$,

$$E_{ijkl} = \frac{2G\nu}{1-2\nu} \delta_{ij} \delta_{kl} + G(\delta_{ik} \delta_{jl} + \delta_{il} \delta_{jk})$$

G 为剪切模量, E, ν 分别为弹性模量及泊松比, δ_{ij} 是 Kronecker 符号。

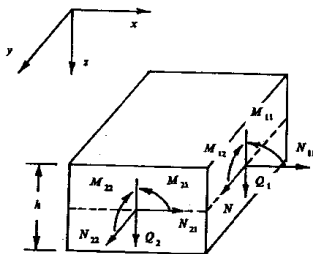


图1 坐标系

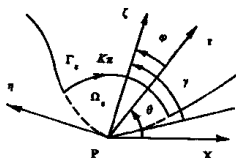


图2 角点局部坐标

弯矩及扭矩 M_{ij} 可由挠度 W 表出

$$M_{ij} = -D[\nu \delta_{ij} W_{,kk} + (1-\nu) W_{,ij}] \quad (5)$$

中面力 N_{ij} 及剪力 Q_i 可表示为

$$\begin{cases} N_{ij} = N_{ij}^{(L)} + N_{ij}^{(N)} \\ N_{ij}^{(L)} = hG \left(u_{i,j} + u_{j,i} + \frac{2\nu}{1-\nu} \delta_{ij} u_{k,k} \right) \\ N_{ij}^{(N)} = hG \left(W_{,i} W_{,j} + \frac{\nu}{1-\nu} \delta_{ij} W_{,k} W_{,k} \right) \end{cases} \quad (6)$$

$$Q_i = -D W_{,kki} \quad (7)$$

如果我们仅考虑较低频率薄板的非线性自由振动, 则中面惯性力项可以略去^[1], 且有 $f = 0$ 。

以 W_1^* 为权函数, 对 (1) 式进行加权积分, 并经过适当的分步积分后, 可得

$$\begin{aligned} C_p W_p + \int_{\Gamma} \left[\left(V_{n1}^* + V_{n1}^{(N)*} \right) W - M_{n1}^* W_n + W_{n1}^* M_n - W_1^* V_n \right] d\Gamma \\ + \sum_{n=1}^{\infty} \left(\|M_{n1}^*\| \|W - W_1^*\| \|M_{nn}\| \right) = \frac{1}{D} \int_{\Omega} \left(W_1^* N_{ij} W - \rho W_1^* W \right) d\Omega \end{aligned} \quad (8)$$

其中, W_n, M_n, M_{nn}, V_n 分别为薄板边界上的法向导数、法向弯矩、扭矩及等效剪

力。 W_1^* 为薄板小挠度弯曲问题的基本解, $W_1^* = \frac{1}{8\pi} r^2 \ln r$; $r = |\rho q|$ 。记 n_l 为方向余弦,

$$V_{n1}^{(N)} = \frac{1}{D} N_{kl} n_l W_{,k}$$

有关挠度场导数的积分方程, 可以对 (8) 式直接微分得到。在图 2 所示的局部坐标系中, 有

$$K_\zeta W_{,\zeta} + K_\eta W_{,\eta} + \int_\Gamma \left[V_{n2}^* (W - W_p) + V_{n2}^{(N)*} W - M_{n2}^* W_n + W_{n2}^* M_n - W_2^* V_n \right] dV \\ + \sum_{i=1}^k \left(\| M_{ni}^* \| \| W - W_2^* \| \| M_{ni} \| \right) = \frac{1}{D} \iint_\Omega \left(W_2^* \cdot_{ij} N_{ij} W - \rho W_2^* \ddot{W} \right) d\Omega \quad (9)$$

其中

$$W_2^* = \frac{1}{8\pi} (1 + 2\ln r) r \cos \varphi$$

$$K_\zeta = -\frac{\kappa}{2} - (\nu / 4\pi) [\sin 2\gamma + \sin 2(\kappa\pi - \gamma)]$$

$$K_\eta = -(\nu / 4\pi) [\cos 2\gamma - \cos 2(\kappa\pi - \gamma)]$$

以线弹性平面应力问题的基本解为权函数, 对 (2) 式进行加权积分, 得^[6]

$$C_p u_i(p) = \int_\Gamma \left(P_k U_{ik}^* - P_{ik}^* u_k \right) d\Gamma - \iint_\Omega N_{ikl}^* e_{kl}^{(N)} d\Omega \quad (10)$$

其中

$$U_{ik}^* = \frac{1+\nu}{8\pi h G} \left(r_i r_{,k} - \frac{3-\nu}{1+\nu} \ln r \delta_{ik} \right)$$

对 (10) 式进行微分, 并合理地处理其高阶奇异性后^[7], 可得域内任意一点 P 处的内力表达式^[6]

$$N_{ij}(p) = \int_\Gamma \left(P_k D_{ijk}^* - S_{ijk}^* u_k \right) d\Gamma - \iint_\Omega T_{ijkl}^* e_{kl}^{(N)} d\Omega + \frac{1}{8} h G (1 + \nu) \left[2\varepsilon_{ij}^{(N)} + \varepsilon_{kk}^{(N)} \delta_{ij} \right] \quad (11)$$

由于我们仅考虑自由振动或谐波激励响应这类周期解问题, 故可以采用谐波平衡法从 (8)~(11) 式中消去时间变量, 得到周期振动的频率与振幅之间的关系式。

设挠度可写成如下形式^[1]

$$W(x, y, t) = \bar{W}(x, y) \tau(t) \quad (12)$$

其中 $\bar{W}(x, y)$ 为振幅函数, 由 (2)、(6) 可得

$$u_i(x, y, t) = \bar{u}_i(x, y) \tau^2(t) \quad (13)$$

将 $\tau(t)$ 展成 Fourier 级数, 作为首次近似, 仅考虑其主谐波分量的平衡, 代入 (8) 式, 并在一个周期内作平均^[1], 得

$$C_p \bar{W}_p + \int_\Gamma \left[\left(V_{n1}^* + V_{n1}^{(N)*} \right) \bar{W} - M_{n1}^* \bar{W}_n + W_{n1}^* \bar{M}_n - W_1^* \bar{V}_n \right] d\Gamma$$

$$+ \sum_{i=1}^K \left(\|M_{nsi}^* \| \bar{W} - W_i^* \| \bar{M}_{ns} \| \right) = \frac{1}{D} \iint_{\Omega} \left(\frac{3}{4} W_i^* \cdot {}_{ij} \bar{N}_{ij} - \rho \omega^2 W_i^* \right) \bar{W} d\Omega \quad (14)$$

同样地, 对 (9)~(11) 式作平均, 各积分方程的形式不变, 只是其中各瞬态场以对应的稳态振幅函数替换之。

三、积分方程的离散及迭代求解

同时对边界及区域内部进行离散, 采用常数插值, 对挠度场积分方程, 依次将源点 P 取在各个边界节点上有

$$[A_1]\{\varphi\} = [B_1]\{N_{ij}W\} + \lambda^2[C_1]\{W\} \quad (15)$$

取源点在各个域内节点上, 得

$$\{W\} + [A_2]\{\varphi\} = [B_2]\{N_{ij}W\} + \lambda^2[C_2]\{W\} \quad (16)$$

$$-\{W_{,i}\} + [A_3]\{\varphi\} = [B_3]\{N_{ij}W\} + \lambda^2[C_3]\{W\} \quad (17)$$

其中, $\lambda = \rho\omega^2 / D$; $\{\varphi\}$ 是与弯曲有关的边界未知参数构成的列向量。

同样, 对中面变形场的积分方程离散后可得

$$[D_1]\{u\} = [R_1]\{\varepsilon_{ij}^{(N)}\} \quad (18)$$

$$\{N_{ij}\} = [D_2]\{u\} + [R_2]\{\varepsilon_{ij}^{(N)}\} \quad (19)$$

(15)~(19) 式给出非线性振动的幅频关系, 经过适当的矩阵运算后, 可得如下广义特征值问题

$$[A]\{W\} = \lambda^2[B]\{W\} \quad (20)$$

其中, 系数矩阵 $[A]$ 与中面内力 $\{N_{ij}\}$ 有关。

求解可以按如下的迭代过程进行:

- (1) 给定挠度 W 的最大值 W_{max} 作为控制参数;
- (2) 设定域内各节点的中面内力 $\{N_{ij}\}$ 初始值; 首次可以赋零, 以后计算的迭代初值可以取前一控制参数值 W_{max} 时的计算结果; 形成代数特征值方程;
- (3) 解广义特征值问题 (20), 求得第 k 次迭代的频率 $\lambda^{(k)}$ 及对应的振型 $\{W\}^{(k)}$;
- (4) 特征向量 $\{W\}^{(k)}$ 规范化, 即以一比例因子乘以求得的特征向量 $\{W\}^{(k)}$, 使之最大挠度值为 W_{max} ; 再求出域内各节点的中面内力 $\{N_{ij}\}$;
- (5) 重复 (2)~(4) 步骤;
- (6) 比较两次结果是否满足收敛判据; 若满足, 则回到 (1), 开始新的计算; 否则, 由 (2) 继续迭代。

四、算例

根据前面推导的公式及提出的迭代方法, 分析计算了多种边界条件组合情况下薄板振动的非线性幅频关系, 考察了不同单元划积分方程解的收敛情况。

例 1. 周边简支方板基频模态的非线性分析。中面边界条件为不可移动, 即 $u_n = P_s = 0$, 数值结果如表 1 所列。 T_0 表示为线性振动周期, T 表示为大挠度非线性振动周期。

例 2. 周边固支方板基频模态的非线性分析。中面边界条件为应力自由, 即 $P_n = P_s = 0$, 数值结果如表 2 所列。

例 3. 各种组合边界条件方板基频模态的非线性分析。各算例均使用 6×6 单元划分, 取板中点挠度为控制参数。数值结果分别列于表 3~6。

表 1 周边简支方板基频模态非线性振动周期比 T/T_0 及收敛性

W/h	0.4	0.8	1.2	1.6	2.0
$Me s h$					
4×4	0.9369	0.7968	0.6499	0.5245	0.4239
6×6	0.9340	0.7912	0.6467	0.5268	0.4311
8×8	0.9324	0.7881	0.6448	0.5283	0.4376

表 2 周边固支方板基频模态非线性振动周期比 T/T_0 及收敛性

W/h	0.4	0.8	1.2	1.6	2.0
$Me s h$					
4×4	0.9940	0.9766	0.9500	0.9173	0.8818
6×6	0.9920	0.9698	0.9359	0.8946	0.8503
8×8	0.9915	0.9674	0.9317	0.8888	0.8431

表 3 三边固定一边简支方板基频模态非线性振动周期比 T/T_0

W/h	0.2	0.4	0.6	0.8	1.0
本文解	0.9916	0.9676	0.9313	0.8864	0.8369
文献[3]	0.994	0.975	0.944	0.905	0.865
文献[4]	0.9907	0.9646	0.9262	0.8807	0.8322

表 4 一对边固定另对边简支方板基频模态非线性振动周期比 T/T_0

W/h	0.2	0.4	0.6	0.8	1.0
本文解	0.9911	0.9655	0.9265	0.8783	0.8251
文献[3]	0.9919	0.9675	0.9307	0.8858	0.8370
文献[4]	0.9904	0.9634	0.9231	0.8750	0.8235

表 5 两邻边固定另两邻边简支方板基频模态非线性振动周期比 T/T_0

W/h	0.2	0.4	0.6	0.8	1.0
本文解	0.9877	0.9535	0.9040	0.8465	0.7806
文献[3]	0.985	0.960	0.912	0.860	0.806
文献[4]	0.9864	0.9499	0.8994	0.8435	0.7881

表6 一边固定三边简支方板基频模态非线性振动周期比 T/T_0

W/h	0.2	0.4	0.6	0.8	1.0
本文解	0.9837	0.9464	0.8900	0.8253	0.7589
文献[3]	0.984	0.954	0.900	0.844	0.784
文献[4]	0.9848	0.9440	0.8877	0.8258	0.7645

本文工作是边界积分方程法应用的新尝试。提供的各数值算例与可供比较的有限元解,符合良好,表明了本文方法的可行性。本文方法,在域内仅需对挠度场本身进行插值离散,避免了有限元方法中的 C^1 类连续问题。

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NONLINEAR VIBRATION ANALYSIS OF ELASTIC THIN PLATES OF COMPLEX BOUNDARY CONDITIONS BY USING BIE METHOD

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Abstract In this paper, an integral equation formulation, based on the Von Karman's nonlinear bending theory, for large amplitude free vibration of thin plates is presented. By using