

大小叶盘-硬涂层阻尼结构的解析建模和振动分析

高峰^{1,2}, 孙伟^{1,2}, 倪陈兵¹

(1. 东北大学 机械工程与自动化学院, 辽宁 沈阳 110819; 2. 东北大学 航空动力装备振动及控制教育部重点实验室, 辽宁 沈阳 110819)

摘 要: 对叶片涂敷 NiCoCrAlY + YSZ 硬涂层, 研究具有硬涂层的大小叶盘的动力学模型和振动特性, 主要研究硬涂层对大小叶盘的阻尼减振性能的影响。首先, 利用复模量理论和 Oberst 梁理论, 建立了涂层大小叶盘结构的解析模型; 然后, 基于 Gram-Schmidt 法和 Rayleigh-Ritz 法, 求解涂层大小叶盘结构的模态特性和受迫响应。结果表明: 硬涂层阻尼对大小叶盘固有频率的影响很小, 但能使模态损耗因子提高 4 倍, 说明硬涂层可以有效提高大小叶盘的阻尼性能; 此外, 涂敷硬涂层可以有效抑制其受迫响应。

关 键 词: 大小叶盘; 硬涂层阻尼; 被动减振; 解析建模; 受迫响应

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Analytical Modeling and Vibration Analysis of Hard-Coated Splitter Blisk

GAO Feng^{1,2}, SUN Wei^{1,2}, NI Chen-bing¹

(1. School of Mechanical Engineering & Automation, Northeastern University, Shenyang 110819, China; 2. Key Laboratory of Vibration and Control of Aero-Propulsion System (Ministry of Education), Northeastern University, Shenyang 110819, China. Corresponding author: SUN Wei, E-mail: weisun@mail.neu.edu.cn)

Abstract: The blades were coated with NiCoCrAlY + YSZ, then the dynamic model and vibration characteristics of the hard-coated splitter blisk were investigated, as well as the effect of hard coating on damping vibration reduction of the splitter blisk. Firstly, analytical model of the hard-coated splitter blisk was obtained using the complex modulus and the Oberst beam theories. The mode characteristics and forced responses of the hard-coated splitter blisk were then solved using the Gram-Schmidt process and Rayleigh-Ritz method. The results reveal that hard coating has a weak effect on natural frequencies of splitter blisk but makes the modal loss factors increase about four times, which explains that hard coating can effectively improve the damping performance of the splitter blisk. Moreover, the forced response can be suppressed remarkably.

Key words: splitter blisk; hard coating; passive vibration reduction; analytical modeling; forced response

在常规叶片通道的后部加入分流叶片, 既可抑制甚至消除大弯度叶片叶背处由于惯性作用造成的气流分离, 又可避免过多的全弦长叶片造成的叶片槽道前部气流堵塞^[1]。近年来, 学者对大小叶盘开展了较深入的研究。Yang 等^[2]研究了分流叶片对双吸式离心泵汽蚀性能的影响; Kassanos 等^[3]研究了带分流叶片的 Francis 水轮机对引流管汽蚀性能的作用; Guo 等^[4]研究了带

分流叶片的离心泵在高速状态下的汽蚀性能; Korkmaz 等^[5]研究了分流叶片对深井泵工作性能的影响, 并求解了最优化组合参数。Torshizi 等^[6]研究了分流叶片轮廓对压气机的影响, 并利用基因优化完成了叶轮结构的多层优化。

大小叶盘的结构阻尼较小, 容易发生疲劳失效, 因此, 需要引入附加阻尼器实现有效减振。由于结构一体化, 传统的干摩擦阻尼器^[7-9]很难应

用在大小叶盘结构上. 研究中常用的黏弹性阻尼^[10]、约束层阻尼^[11]和压电阻尼^[12]的阻尼性能往往因无法承受高温、高压和强腐蚀等而失效. 硬涂层具有较高硬度^[13], 耐高温、耐摩擦、耐腐蚀^[14-16], 还具有较好的阻尼能力. Yang 等^[17]基于有限元法求解了涂敷 NiCrAlY 硬涂层的 Mg-Al 合金板的固有特性. Sun 等^[18]利用能量法求解了涂敷 MgO + Al₂O₃ 涂层的悬臂梁的振动特性; Zhang 等^[19]分析了涂敷硬涂层的薄壁圆柱壳在不同约束下的振动特性.

本文对叶片涂敷 NiCoCrAlY + YSZ 硬涂层, 并分析大小叶盘－硬涂层阻尼结构的振动特性. 首先, 引入气动弹簧来考虑叶片与轮盘的耦合关系, 并基于复模量和 Oberst 梁理论建立了涂层大小叶盘的解析模型; 然后, 基于 Gram-Schmidt 法和 Rayleigh-Ritz 法求解了涂层大小叶盘的模式特性和受迫响应, 重点研究了硬涂层对大小叶盘的阻尼减振性能.

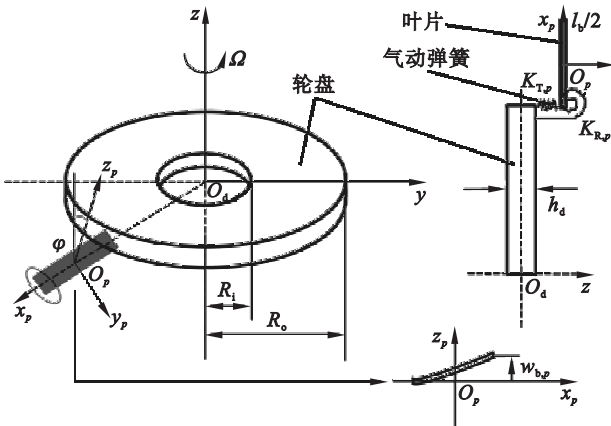
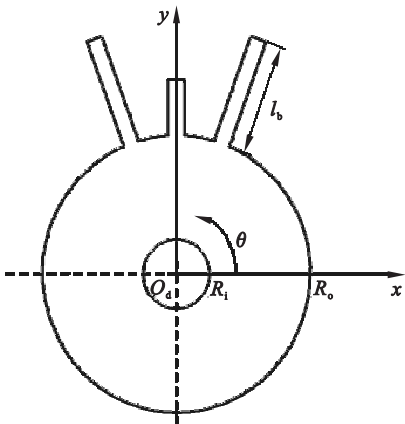


图 1 大小叶盘－硬涂层阻尼结构的解析模型
Fig. 1 Analytical model of the hard-coated splitter blisk

1.2 叶片－硬涂层阻尼结构的等效参数求解

将复合结构等效成属性均匀的单一结构, 可以在不降低计算精度的前提下极大地简化计算过

程^[20]. 图 2 所示为涂层叶片原理图和复合 Oberst 梁截面图.

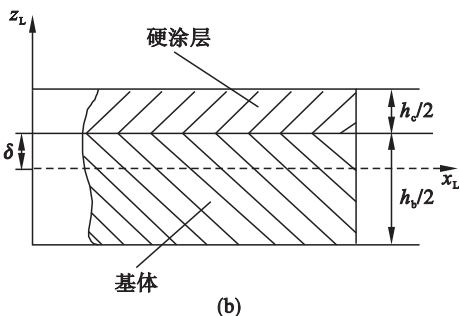
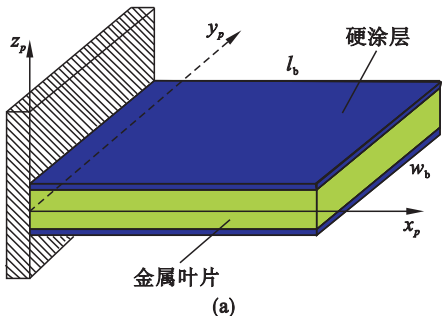


图 2 叶片－硬涂层阻尼结构
Fig. 2 Structure of hard-coated blade
(a)－原理图; (b)－截面图.

叶片和硬涂层的复弹性模量 E_b^* 和 E_c^* 分别表示为

$$E_b^* = E_b + E'_b = E_b(1 + i\eta_b), \quad (1)$$

$$E_c^* = E_c + E'_c = E_c(1 + i\eta_c). \quad (2)$$

式中: $i = \sqrt{-1}$; 下脚标 b 和 c 分别表示叶片和硬涂层阻尼; E 和 E' 分别表示弹性(储能)模量和耗能模量; η 表示材料损耗因子。

当复合梁在纯弯曲状态时, 其平衡方程表示为

$$\int_{-\left(\frac{h_b}{2}-\xi\right)}^{\xi} E_b z_L dz_L + \int_{\xi}^{\frac{h_c}{2}+\xi} E_c z_L dz_L = 0, \quad (3)$$

则中性面到结合面的距离 ξ 为

$$\xi = (E_b h_b^2 - E_c h_c^2) / [4(E_b h_b + E_c h_c)]. \quad (4)$$

复合梁的复截面弯矩 M^* 可以表示为

$$M^* = \frac{B^*}{i\omega} \frac{\partial \tilde{\omega}}{\partial x_L} =$$

$$\frac{w_b}{i\omega} \frac{\partial \tilde{\omega}}{\partial x_L} \left[\int_{-\left(\frac{h_b}{2}-\xi\right)}^{\xi} E_b^* z_L^2 dz_L + \int_{\xi}^{\frac{h_c}{2}+\xi} E_c^* z_L^2 dz_L \right]. \quad (5)$$

式中: $\tilde{\omega}$ 表示复合梁的侧向角速度; B^* 表示复合梁的复弯曲刚度:

$$B^* = \frac{w_b}{6} \left[E_b^* \left(3\xi^2 h_b - \frac{3}{2}\xi h_b^2 + \frac{1}{4}h_b^3 \right) + E_c^* \left(3\xi^2 h_b + \frac{3}{2}\xi h_c^2 + \frac{1}{4}h_c^3 \right) \right]. \quad (6)$$

定义无量纲量 $\frac{E_c^*}{E_b^*} = e^*$, $\frac{E_c}{E_b} = e$ 和 $\frac{h_c}{h_b} = h_e$, 将

式(4)代入式(6)并整理可得

$$B^* = \frac{E_c^* w_b h_b^3}{12} \left(\frac{1 + 4e^* h_e + 6e^* h_e^2 + 4e^* h_e^3 + e^{*2} h_e^4}{1 + e^* h_e} \right). \quad (7)$$

根据文献[21], 由式(7)可得复合梁的等效复模量 E_e^* 、弹性模量 E_e 和材料损耗因子 η_e , 分别为

$$E_e^* = E_e(1 + i\eta_e), \quad (8)$$

$$E_e = \frac{1 + 4eh_e + 6eh_e^2 + 4eh_e^3 + e^2 h_e^4}{(1 + eh_e)(1 + h_e^3)} E_b, \quad (9)$$

$$\eta_e = \eta_b + \frac{eh_e}{1 + eh_e} \frac{3 + 6h_e + 4h_e^2 + 2eh_e^2 + e^2 h_e^4}{1 + 4eh_e + 6eh_e^2 + 4eh_e^3 + e^2 h_e^4} (\eta_c - \eta_b). \quad (10)$$

此外, 大叶片-硬涂层阻尼结构的等效密度 ρ_e 为

$$\rho_e = (\rho_b h_b + \rho_c h_c) / (h_b + h_c). \quad (11)$$

式中, ρ_b 和 ρ_c 分别表示叶片和硬涂层的密度. 小涂层叶片的等效弹性模量 E_e 、材料损耗因子 η_e 和密度 ρ_e 可同理求得.

1.3 大小叶盘-硬涂层阻尼结构的振动分析

在旋转态下, 气动弹簧的势能 V_s 表示为

$$V_s = \frac{1}{2} \sum_{p=1}^P \left[K_{T,p} (w_d - w_{b,p} \cos \varphi_p)^2 + K_{R,p} \left(\frac{\partial w_d}{\partial r} - \frac{\partial w_{b,p}}{\partial r} \cos \varphi_p \right)^2 \right]_{r=R_o, \theta=\theta_p}. \quad (12)$$

涂层叶片的应变能 U_e^* 、势能 V_e 和动能 T_e 分别为

$$U_e^* = \frac{1}{12} \sum_{p=1}^P E_e^* w_b (h_b + h_c)^3 \int_{-\frac{l}{2}}^{\frac{l}{2}} \frac{\partial^2 w_{b,p}}{\partial x_p^2} dx_p, \quad (13)$$

$$V_e = \frac{\Omega^2 \rho_e}{2} \sum_{p=1}^P A_p \int_{-l/2}^{l/2} \left\{ \frac{\partial w_{b,p}}{\partial x_p} \left[\left(R_o + \frac{l}{2} \right) (R_o - x_p) + \frac{1}{2} \left(\frac{l^2}{4} - x_p^2 \right) \right] - w_{b,p}^2 \sin^2 \varphi \right\} dx_p, \quad (14)$$

$$T_e = \frac{1}{2} \rho_e \sum_{p=1}^P A_p \int_{-\frac{l}{2}}^{\frac{l}{2}} \left(\frac{\partial w_{b,p}}{\partial t} \right)^2 dx_p. \quad (15)$$

轮盘的应变能 U_d^* 、动能 T_d 和势能 V_d 分别为

$$U_d^* = \frac{E_b^* h_b^3}{24(1-\nu^2)} \int_{R_i 0}^{R_o 2\pi} \left\{ \left(\frac{\partial^2 w_d}{\partial r^2} + \frac{1}{r} \frac{\partial w_d}{\partial r} + \frac{1}{r^2} \frac{\partial^2 w_d}{\partial \theta^2} \right)^2 - 2(1-\nu) \left\{ \frac{\partial^2 w_d}{\partial r^2} \left(\frac{\partial w_d}{r \partial r} + \frac{\partial^2 w_d}{r^2 \partial \theta^2} \right) - \left[\frac{\partial}{\partial r} \left(\frac{\partial}{r \partial \theta} \right) \right]^2 \right\} \right\} r d\theta dr, \quad (16)$$

$$T_d = \frac{1}{2} \rho_d h_d \int_{R_i 0}^{R_o 2\pi} \left(\frac{\partial w_d}{\partial t} \right)^2 r d\theta dr, \quad (17)$$

$$V_d = \frac{h_d}{2} \int_{R_i 0}^{R_o 2\pi} \left[\sigma_r \left(\frac{\partial w_d}{\partial r} \right)^2 + \sigma_\theta \left(\frac{\partial w_d}{r \partial \theta} \right)^2 \right] r d\theta dr. \quad (18)$$

式中: ν 表示轮盘结构的泊松比, σ_r 和 σ_θ 分别表示旋转态时轮盘结构的径向力和周向力, 且

$$\left\{ \begin{aligned} \sigma_r &= \frac{E_b}{1-\nu^2} \left(\nu \frac{u}{r} + \frac{du}{dr} \right), \\ \sigma_\theta &= \frac{E_b}{1-\nu^2} \left(\frac{u}{r} + \nu \frac{du}{dr} \right). \end{aligned} \right. \quad (19)$$

式中, u 表示轮盘结构的径向位移, 且有

$$\left. \begin{aligned} u &= C_1 r + C_2 r^{-1} - \frac{1-\nu^2}{8} \rho_d r^3 \Omega^2, \\ C_1 &= \frac{(1-\nu^2) \rho_d \Omega^2}{8 E_b [(1+\nu) R_o^2 + (1-\nu) R_i^2]} \left\{ [(3+\nu) R_o^4 + (1-\nu) R_i^4] + \right. \\ &\quad \left. 2 R_o^2 (R_o^2 - R_i^2) \frac{2 m_b R_o + P \rho_d A_p l^2}{m_d R_o} \right\}, \\ C_2 &= \frac{(1-\nu^2) \rho_d \Omega^2 R_o^2 R_i^2}{8 E_b [(1+\nu) R_o^2 + (1-\nu) R_i^2]} \left\{ [(3+\nu) R_o^4 - (1+\nu) R_i^4] - \right. \\ &\quad \left. 2 R_o^2 (R_o^2 - R_i^2) \frac{2 m_b R_o + P \rho_d A_p l^2}{m_d R_o} \right\}. \end{aligned} \right\} \quad (20)$$

式中, m_b 和 m_d 分别表示涂层叶片和轮盘的质量.

令无量纲量 $a = r/R_o$, $b_p = x_p/l$, 当大小叶盘以频率 ω 自由振动时, 根据小变形理论的运动叠加原理, 轮盘和叶片阻尼结构的位移方程分别为

$$w_d(r, \theta, t) = R_o W_d(a, \theta) \sin(\omega t), \quad (21)$$

$$w_{b,p}(x_p, t) = R_o W_{b,p}(b_p, \theta) \sin(\omega t). \quad (22)$$

式中, W_d 和 $W_{b,p}$ 分别表示轮盘和涂层叶片的振型:

$$W_d(a, \theta) = \sum_{m=1}^M \sum_{n=0}^N \Phi_m(a) [A_m^c \cos(n\theta) + A_m^s \sin(n\theta)]. \quad (23)$$

$$W_{b,p}(b_p) = \sum_{r_p=1}^{R_p} B_{r_p} \Psi_{r_p}(b_p). \quad (24)$$

式中: A_m^c , A_m^s 和 B_{r_p} 是待定系数; A_m^c 和 A_m^s 对应于轮盘的对称、反对称模态; n 表示轮盘节径数; N 为轮盘最大节径数; M 和 R_p 分别是轮盘和涂层叶片 Ritz 基维数, Φ_m 和 Ψ_{r_p} 是 Gram - Schmidt 法构造的正交多项式.

将能量公式(11) ~ (20) 代入拉格朗日方程, 可得

$$L = T_e + T_d - (V_s + U_e^* + U_d^* + V_e + V_d). \quad (25)$$

根据最小势能原理, 系统位移状态的广义坐标应能使系统位能取得最小值 L_{\min} , 即

$$\left. \begin{aligned} \partial L / \partial A_m^c &= 0, \\ \partial L / \partial A_m^s &= 0, \\ \partial L / \partial B_{r_p} &= 0. \end{aligned} \right\} \quad (26)$$

则大小叶盘－硬涂层阻尼结构的特征方程表示为

$$(\mathbf{K}^* - \lambda_*^2 \mathbf{M}) \mathbf{X} = \mathbf{0}, \quad (27)$$

$$\mathbf{X} = [A_m^c, A_m^s, B_{r_p}]^T. \quad (28)$$

式中: \mathbf{M} 和 \mathbf{K}^* 分别表示大小叶盘－硬涂层阻尼结构的质量和复刚度矩阵; \mathbf{X} 表示正则化振型向量; λ_* 为复特征值. 则其固有频率 ω 和模态损耗因子 η 分别为

$$\left. \begin{aligned} \omega &= \operatorname{Re} \sqrt{\lambda_*}, \\ \eta &= \operatorname{Im}(\lambda_*) / \operatorname{Re}(\lambda_*). \end{aligned} \right\} \quad (29)$$

由于硬涂层具有非常好的稳定性, 所以大小叶盘－硬涂层阻尼结构的刚度矩阵 \mathbf{D} 通过 Rayleigh 阻尼模型^[22] 间接求得, 即

$$\mathbf{D} = \alpha \mathbf{M} + \beta \operatorname{Re}(\mathbf{K}^*), \quad \alpha + \beta \omega_j^2 = \eta_j \omega_j. \quad (30)$$

式中下标 j 为模态阶次.

大小叶盘－硬涂层阻尼结构的频域响应函数为 Z :

$$Z = \sum_{j=1}^J \frac{\mathbf{X}_j^T \mathbf{F} \mathbf{X}_j}{\omega_j^2 + i \eta_j \omega_j - \omega^2}. \quad (31)$$

式中, \mathbf{F} 和 ω 分别表示外部激励力和激励频率.

2 实例研究

2.1 大小叶盘－硬涂层阻尼结构的基本参数

图 3a 为大小叶盘的连续参数试件, 轮盘内径 25 mm, 外径 100 mm, 厚度 3 mm; 大叶片长度 80 mm, 宽度 24 mm; 小叶片长度 40 mm, 宽度 24 mm; 叶片厚度均为 3 mm; 气动弹簧平动和转动刚度均为 10^6 N/m. 硬涂层单层涂敷厚度 0.1 mm, 如图 3b 所示. 表 1 所列为大小叶盘和硬涂层的材料参数.

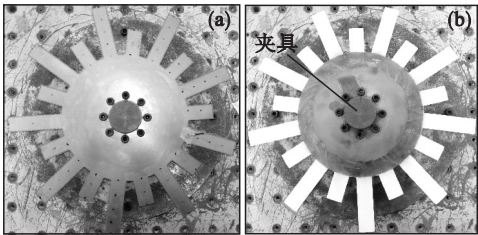


图 3 大小叶盘和大小叶盘－硬涂层阻尼结构
Fig. 3 Splitter blisk with or without hard-coating damper

(a) 一无涂层叶盘; (b) 一带涂层叶盘.

2.2 大小叶盘－硬涂层阻尼结构的振动特性

为了校核解析模型的有效性, 本文还进行了有限元分析和试验测试. 其中, 有限元模型采用

SOLID185 单元划分, 共有 53 316 个单元和 68 436个节点.

图 4 所示为不同途径得到的大小叶盘 – 硬涂层阻尼结构的固有频率. 可以看到, 三组数据之间存在误差, 主要因为: ①有限元法精度受到网格类型和单元属性等因素影响; ②试验测试精度受到测试方法和环境的影响. 但是, 这些误差保持在一定范围内. 此外, 三组数据在整体上的走势非常相似, 这说明解析分析的数据精度是有保证的.

表 1 大小叶盘 – 硬涂层阻尼结构的力学参数
Table 1 Mechanical parameters of hard-coated splitter blisk

参数	大小叶盘	硬涂层
材料	Q235 – A (F)	NiCoCrAlY + YSZ
密度/($\text{kg}\cdot\text{m}^{-3}$)	7 900	5 600
弹性模量/GPa	210	54. 5
损耗因子	0. 30	0. 30
泊松比	0. 000 6	0. 021 2

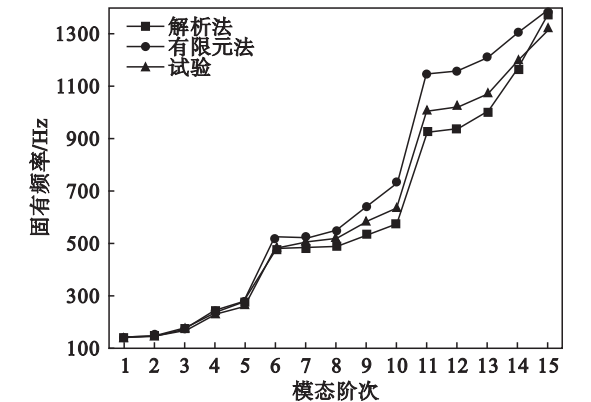


图 4 大小叶盘 – 硬涂层阻尼结构固有频率
Fig. 4 Natural frequency of hard-coated splitter blisk

图 5 所示为解析分析与有限元分析 (A&F) 以及解析分析与试验测试 (A&T) 间的模态置信因子 (MAC). 可以看到, A&F 的 MAC 值普遍大于 0. 975, 说明两者具有非常好的相关性; 由于不理想的试验环境, A&T 的 MAC 值均小于 A&F, 但仍大于 0. 920, 两者间的相关性较好.

3 硬涂层阻尼对大小叶盘的影响

表 2 和表 3 分别是由解析分析和试验测试得到的大小叶盘和大小叶盘 – 硬涂层阻尼结构的固有频率及其变化率. 从中可以发现, 大小叶盘的固有频率在涂敷硬涂层阻尼后全都普遍变小, 但是其变化量并不是很大, 变化率绝对值分别在 1. 27% ~ 2. 61% 和 2. 24% ~ 6. 52% , 说明涂敷硬

涂层阻尼并不会对大小叶盘的固有频率造成显著的影响.

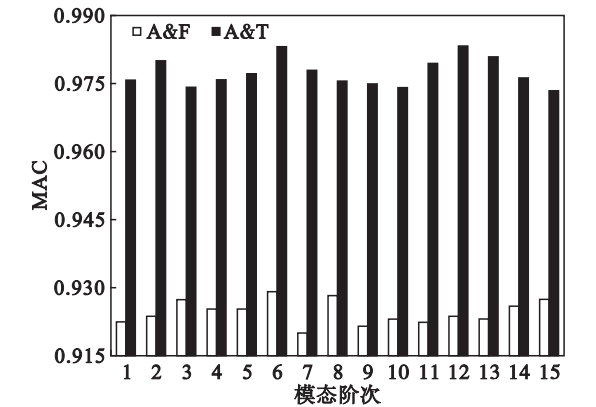


图 5 大小叶盘 – 硬涂层阻尼结构的模态置信因子
Fig. 5 MAC of hard-coated splitter blisk

表 2 解析分析得到的固有频率
Table 2 Natural frequencies of splitter blisk by analytical approach

模态阶次	无涂层结构	硬涂层结构	变化率/%
1	143. 05	139. 97	- 2. 20
2	150. 52	147. 26	- 2. 21
3	172. 93	168. 58	- 2. 58
4	240. 72	237. 71	- 1. 27
5	284. 58	279. 19	- 1. 93
6	480. 41	462. 57	- 3. 86
7	485. 78	468. 95	- 3. 59
8	494. 65	481. 41	- 2. 75
9	538. 46	520. 72	- 3. 41
10	579. 24	563. 84	- 2. 73
11	926. 65	914. 46	- 1. 33
12	941. 68	925. 73	- 1. 72
13	1 010. 87	990. 51	- 2. 06
14	1 172. 45	1 157. 26	- 1. 31
15	1 378. 48	1 347. 18	- 2. 32

表 3 试验测试得到的固有频率
Table 3 Natural frequency of splitter blisk by the test

模态阶次	无涂层结构	硬涂层结构	变化率/%
1	143. 01	135. 77	- 5. 33
2	150. 82	141. 59	- 6. 52
3	171. 04	163. 27	- 4. 76
4	237. 05	225. 57	- 5. 09
5	274. 88	259. 94	- 5. 75
6	480. 09	463. 50	- 3. 58
7	497. 65	483. 10	- 3. 01
8	508. 99	487. 69	- 4. 37
9	562. 33	533. 09	- 5. 49
10	607. 49	574. 82	- 5. 68
11	965. 98	932. 07	- 3. 64
12	982. 12	960. 13	- 2. 29
13	1 040. 30	1 013. 82	- 2. 61
14	1 184. 21	1 158. 24	- 2. 24
15	1 348. 50	1 316. 07	- 2. 46

图 6 所示是大小叶盘和大小叶盘－硬涂层阻尼结构的模态损耗因子. 可以发现, 由于外部干扰, 试验模态损耗因子略大于解析模态损耗因子, 但是, 试验结果与解析结果具有相似的整体变化趋势. 重要的是, 涂敷硬涂层阻尼后大小叶盘的模态损耗因子增大了约 4 倍, 说明硬涂层可以有效提高大小叶盘的阻尼性能.

图 7 是由解析分析得到的大小叶盘和大小叶盘－硬涂层阻尼结构在阶次激励下的受迫响应. 可以看到, 涂敷硬涂层后, 大小叶盘的受迫响应峰值全都明显减小, 说明大小叶盘在共振区域的受迫振动响应被硬涂层显著抑制.

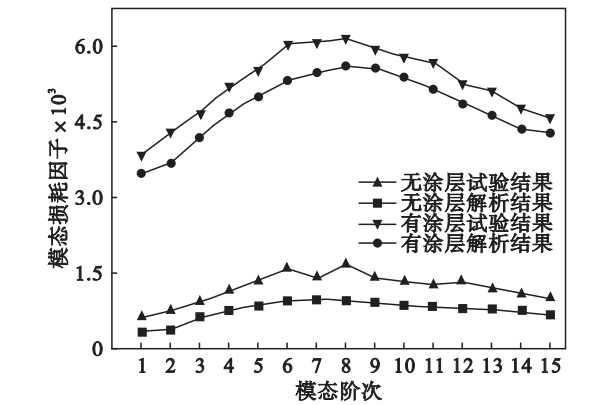


图 6 大小叶盘和大小叶盘－硬涂层阻尼结构模态损耗因子

Fig. 6 Modal loss factor of the splitter blisk with or without hard coating

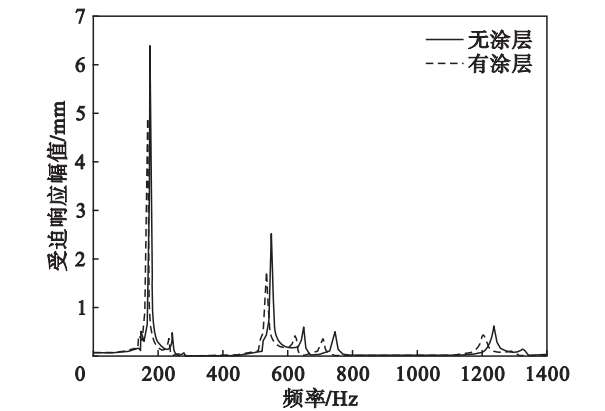


图 7 结构在阶次激励下的受迫响应

Fig. 7 Forced response of splitter blisk under engine order excitation

4 结 论

- 1) 利用复模量理论和能量法建立了大小叶盘－硬涂层阻尼结构的解析模型, 并利用 Ritz 法和 Rayleigh 阻尼模型求解其在阶次激励下的受迫响应.
- 2) 发现 NiCoCrAlY + YSZ 硬涂层不会对大

小叶盘的固有频率造成很大影响, 但会使其模态损耗因子提高约 4 倍, 能有效提高其阻尼性能, 并使其受迫响应峰值明显减小, 实现大小叶盘的有效减振.

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5 结 论

1) 脆性材料车削表面粗糙度由几何干涉粗糙度和脆性崩碎粗糙度组成. 刀具几何形状和进给量主要影响几何干涉粗糙度; 工件力学性能、切削速度、切削深度和切削力主要影响脆性崩碎粗糙度.

2) 刀具对工件材料的挤压会在表面诱发裂纹, 而刀具与工件的相对运动造成了裂纹的扩展与切屑的断裂. 脆性材料车削表面形貌是切屑单元周期性断裂的结果.

3) 氟金云母陶瓷车削表面粗糙度随切削速度的增大而减小, 随进给量的增大而增大, 随切削深度的增大而增大. 脆性材料粗糙度理论模型能够很好地预测趋势, 与传统的几何模型相比, 更接近实验值.

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