

多级组合盘的整体结构最优化设计

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【摘要】 整体组合盘结构优化设计是单级盘结构优化设计的进一步发展,它具有广泛的实用价值。本文采用自动形状描述、单级盘有限元强度计算、多级盘优化协调组合和整体组合盘结构优化设计策略,编制了SODMROD软件,并给出了计算实例。同时介绍了盘剖面形状描述的基本思路和部分公式以及利用优化方法进行盘、鼓间变形协调计算的部分公式推导。

关键词: 多级盘 结构设计 最优化 有限元法

分类号: V232.3

1 引言

航空发动机轮盘的结构设计要求在保证可靠性的情况下,重量尽可能轻。轮盘结构的最优化设计是实现这一思想的最好途径。通常人们只研究单级盘的结构优化设计,而发动机中常以多级组合盘的结构形式出现。由于盘、鼓间组合协调力的作用,使每个盘的受力情况和应力分布与单级盘有所不同。因此,研究多级组合盘的结构优化设计更具有实际价值。

SODMROD(多级组合盘结构优化设计)软件具有多种功能,主要有单级、多级盘有限元网格自动细化;单级、多级盘在离心力场以及变温场下的弹性有限元应力计算;多级盘之间协调力计算;单级、多级盘的全域结构优化设计;转子叶片以及轮缘凸块的离心外载计算;利用I-DEAS后处理软件显示轮盘优化前、后的网格图,应力云图以及变形图等。该软件在程序处理上,对每个轮盘分别进行形状描述、单独进行八节点环单元的有限元强度计算^[1,2],采用优化方法进行盘、鼓间接触面的变形协调计算,将协调组合成的整体盘进行结构最优化设计。形状描述模块和有限元强度计算模块均为独立模块,接触协调计算模块和优化计算模块调用上述两独立模块实现各种计算功能。因此,不仅程序的功能强,结构亦比较清晰,易于修改扩充。

本文着重阐述轮盘的形状描述与优化变量选择之间的关系以及盘、鼓间变形协调的优化处理方法。

2 基本原理与公式

2.1 形状描述及优化变量选择

结构形状优化中很重要的一个过程是形状自动描述,即通过一组优化变量来描述结构形状,并形成新的有限元网格,进行强度分析。因此,形状描述是优化计算与有限元强度计算之间不可缺少的环节。

SODMROD 软件是采用直线—圆弧组合形式的形状描述,其基本组合形式大体可分为:(1)直线与直线相交;(2)直线与圆弧相交;(3)直线与圆弧相切;(4)圆弧与圆弧相交;(5)圆弧与圆弧相切等五种。通过上述诸种形式组合,轮盘剖面形状即可确定,所有的交点和切点也被唯一确定。一旦这些交点和切点变化,轮盘形状也随之发生变化。因此,如果规定这些交点和切点为特征点,则优化变量就可可在这些特征点中人为选取。

2.2 盘、鼓间的协调

采用优化方法进行多级盘的盘、鼓间变形协调计算是本文的特点之一。其中,求变形协调目标函数梯度和一维搜索是协调计算的主要过程。SODMROD 软件利用接触边界平衡条件建立了接触协调目标函数,再利用功的互等定理建立一种简单的求梯度方法,实际应用表明大大减少了求导计算时间。

2.2.1 基本原理

有 a 、 b 两个盘。设它们接触面上有 n 个节点对。若第 j 节点对所受作用力为 X ,使 a 盘的 i 节点产生 $f_{aij}(X)$ 的位移;使 b 盘的 i 节点产生 $f_{bij}(X)$ 的位移,则

目标函数

$$F(X) = \sum_{i=1}^n \sum_{j=1}^n [f_{aij}(X) - f_{bij}(X)] = \sum_{i=1}^n \sum_{j=1}^n \Delta_{ij} \quad (1)$$

其中位移下角标规则是,第一个下角标表示产生位移的节点,第二个下角标表示产生位移的载荷作用节点。第 i 节点对间的位移差为

$$\Delta_i = \sum_{j=1}^n \Delta_{ij} \quad (2)$$

目标函数在 $X^{(k)}$ 作用下的梯度为

$$\nabla F(X^{(k)}) = \left\{ \frac{\partial F(X^{(k)})}{\partial x_1}, \frac{\partial F(X^{(k)})}{\partial x_2}, \dots, \frac{\partial F(X^{(k)})}{\partial x_i}, \dots, \frac{\partial F(X^{(k)})}{\partial x_n} \right\}^T \quad (3)$$

$$\text{式中} \quad \frac{\partial F(X^{(k)})}{\partial x_i} = \frac{\partial}{\partial x_i} \left(\sum_{j=1}^n \sum_{i=1}^n \Delta_{ij} \right) = \sum_{j=1}^n \frac{d\Delta_{ji}}{dx_i} \quad (4)$$

由(3)式可看出,若采用前差分法求梯度,通常进行 $n+1$ 次的有限元强度计算。根据功的互等定理 $x_i f_{ij} = x_j f_{ji}$,其增量表达式为 $df_{ij}/dx_j = df_{ji}/dx_i$,同样

$$d\Delta_{ij}/dx_j = d\Delta_{ji}/dx_i \quad (5)$$

将(5)式代入(4)得

$$\frac{\partial F(X^{(k)})}{\partial x_i} = \sum_{j=1}^n \frac{d\Delta_{ji}}{dx_i} = \sum_{j=1}^n \frac{d\Delta_{ij}}{dx_j} \quad (6)$$

令所有载荷微分 dx_j 相等,即 $dx = dx_j, j = 1, \dots, n$,并将(2)式代入,则(6)式可化为

$$\sum_{j=1}^n \frac{d\Delta_{ij}}{dx_j} = \frac{d}{dx} \left(\sum_{j=1}^n \Delta_{ij} \right) = \frac{d\Delta_i}{dx} \quad (7)$$

将式(6)和(7)代入式(3)得

$$\nabla F(X^{(k)}) = \{ (d\Delta_1/dx) (d\Delta_2/dx) \dots (d\Delta_i/dx) \dots (d\Delta_n/dx) \}^T \quad (8)$$

由(8)式可知,若同时对 n 个接触节点对施加载荷增量 dx ,根据叠加原理, n 个接触节点对的位移差增量分别为 $d\Delta_i (i = 1, 2, \dots, n)$ 。因此,只需进行一次差分增量计算,即可求得接触协调函数的梯度。

2.2.2 迭代步骤

(1) 取初始载荷 $X^{(1)} = 0, k = 1$ 计算 $F(X^{(1)})$ 。

(2) 计算 $\nabla F(X^{(k)})$, $S^{(k)} = -\nabla F(X^{(k)})$ 。

(3) 进行一维搜索, 求最优步长 $\alpha^{(k)}$ 。

$$\min F(X^{(k)} + \alpha S^{(k)}) = f(X^{(k)} + \alpha^{(k)} S^{(k)}) = F(X^{(k+1)})$$

(4) 检查是否满足收敛准则 $|F(X^{(k+1)}) - F(X^{(k)})| \leq \epsilon$ 。

若满足, 则停止迭代, 得到的 $X^{(k+1)}$ 及函数值 $F(X^{(k+1)})$ 为最终协调结果。否则 $k = k + 1$ 转到步骤(2)。

2.3 结构优化

SODMROD 软件中的结构优化方法采用复合形法^[3,4], 它是求解约束非线性最优化问题的一种直接优化方法, 对于结构优化设计问题很有效。该软件以轮盘重量 $G(X)$ 为目标函数, 应力标准为约束^[5], 数学模型为(在 n 维空间 E^n 中的可行域 & 下)

$$\min G(X) \quad X \in \& \subset E^n$$

约束函数: $n_{\theta 1} = \bar{\sigma}_{\theta 1} / \sigma_{0.1} \leq [n_{\theta 1}]$, $n_r = \sigma_r / \sigma_{0.1} \leq [n_r]$, $n_{\theta 2} = \sigma_{\theta 腹} / \sigma_{0.1} \leq [n_{\theta 2}]$, $n_{\theta 3} = \sigma_{\theta 心} / \sigma_{0.1} \leq [n_{\theta 3}]$, $\delta_{缘} \leq [\delta_{缘}]$ 。其中, $\bar{\sigma}_{\theta}$ 为轮盘平均周向应力; σ_r 为轮盘最大径向应力; $\sigma_{\theta 腹}$ 为轮盘腹板的最大周向应力; $\sigma_{\theta 心}$ 为轮盘内径上的最大周向应力; $\sigma_{0.1}$ 为材料屈服强度极限; $\delta_{缘}$ 为轮盘外缘最大径向位移; $[n]$ 和 $[\delta]$ 为许用值。变量 X 可根据实际情况, 在形状描述的特征点中选取。

3 计算实例

用 SODMROD 软件对某发动机的三级组合盘进行了组合结构的优化设计(对盘的腹板及轮毂的厚度进行优化)。在 VAX-6410 计算机上占用的 CPU 时间约 4 个小时。优化前、后的结构及其主应力图见图 1 和 2(图 1 中应力 1 为 114.15, 2 为 164.39, 3 为 214.63, 4 为 264.27, 5 为 315.11, 6 为 365.35。图 2 中应力 1 为 107.4, 2 为 200.57, 3 为 261.34, 4 为 313.10, 5 为 364.87, 6 为 416.63), 计算结果见表 1 和 2。由图 2 可见, 对于优化后的盘, 腹板主要承受径

应力 MIN: 63.92
MAX: 415.58

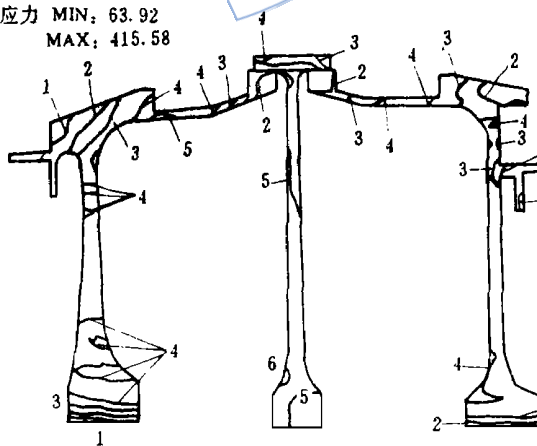


图 1 优化前结构及主应力图

应力 MIN: 106.04
MAX: 468.40

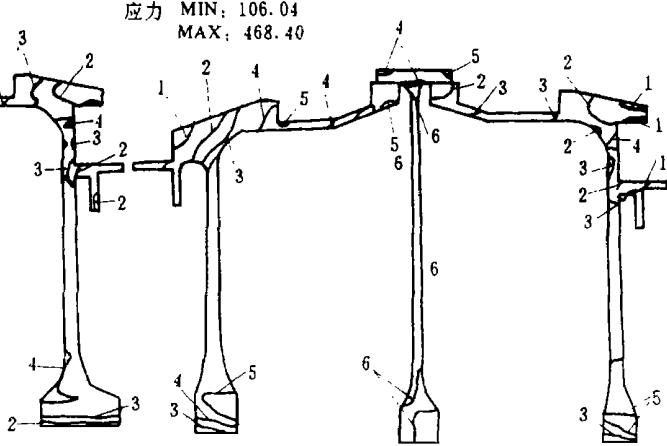


图 2 优化后结构及主应力图

向应力, 轮毂主要承受周向应力。

由表1 看出,第1 级和第3 级盘的最大径向应力 σ_r 已达到许用值,第2 级盘的轮缘径向位移 $\delta_{r\text{缘}}$ 已达到许用值,总重量由 29. 931kg 减到 24. 709kg,降低了 17. 45%。

表 1 优化前后计算结果

	级数	重量(kg)	n_{e1}	n_r	n_{e2}	n_{e3}	$\delta_{r\text{缘}}$
许用值			0. 8	0. 8	0. 85	0. 95	1
优化前	1	12. 648	0. 3517	0. 4971	0. 4286	0. 5909	0. 7730
	2	6. 597	0. 4667	0. 4566	0. 5052	0. 5733	0. 7761
	3	10. 686	0. 3222	0. 6583	0. 4462	0. 4733	0. 7215
优化后	1	10. 578	0. 4278	0. 7978	0. 6426	0. 7440	0. 8541
	2	4. 587	0. 5979	0. 6386	0. 6841	0. 6626	0. 9988
	3	9. 543	0. 3866	0. 7997	0. 6077	0. 9167	0. 6827

由表2 可见,优化前后,两个协调面的6 个协调节点对中,只有4 个节点对接触,接触点的位移协调精度均小于 $1\mu\text{m}$ 。

表 2 组合轮盘间的协调结果

			第 1、2 级盘的协调面			第 2、3 级盘的协调面		
协调节点对序号			1	2	3	4	5	6
前一级盘上的节点号			106	109	114	23	26	27
后一级盘上的节点号			25	24	21	95	90	87
优化前	径向位移差(mm)	0. 00026	0. 00009	0. 16163	0. 00034	0. 00036	0. 16084	
	接触压力(N/mm)	3. 184	93. 233	0. 0	16. 871	84. 029	0. 0	
优化后	径向位移差(mm)	0. 33341	0. 00001	0. 00004	0. 00001	0. 00006	0. 16512	
	接触压力(N/mm)	0. 0	46. 032	20. 726	8. 689	36. 719	0. 0	

结论 (1)SODMROD 软件对实际盘的结构优化是有效的。(2)改进后的变形协调目标函数的梯度计算方法,不仅减少了计算机时,而且求导效果也比通常的差分法好。

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TRANSIENT CHARACTERISTICS OF A FLEXIBLE ROTOR SUPPORTED ON NONLINEAR SFD'S THROUGH BISTABLE OPERATION RANGE

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ABSTRACT

The transient characteristics of a flexible rotor supported on nonlinear squeeze film dampers (SFD's) during passing through the resonant and bistable operation speed range with constant acceleration are studied theoretically and experimentally. It is shown that the properly designed SFD's have not only excellent steady-state performance, but also better acceleration performance. The maximum vibration amplitude of the rotor system in the acceleration process decreases gradually with increase of rotor angular acceleration, whether for the properly designed SFD's or for the improperly designed SFD's. The stability of multistable operation in the bistable operation speed ranges depends not only on the form of bistable operation, but also on the moving process. It is impossible for the rotor system to pass through the bistable operation speed ranges with smaller amplitudes only by means of accelerating the rotor system.

Key words Rotors Dampers Transient response Dynamic characteristics

CALCULATION ON FLEXIBILITY MATRIX AND MODIFICATION OF HELICAL GEARS BY FEM

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ABSTRACT

A computer program is worked out for modification design of helical gears by using Finite Element Method (FEM). At first the finite element mesh of gear tooth is auto-generated without engagement of gears, therefore it can be divided more conveniently and uniformly. The flexibility matrixes of mesh nodes on working flanks of gears are calculated by FEM. Then, the contact lines and contact nodes on the plane of action are generated by computer according to the contact ratio of gear pair. The flexibility matrixes of contact nodes are obtained by interpolation between the mesh nodes on plane of action. Further, the deformation of shafts and bearings is added to the total flexibility matrix which is sum of the flexibility matrixes of both gears. Finally, considering minimization of transmitting error and uniformization of load density as objective functions, an optimal 3-D modification is solved by using mathematical programming technique. Moreover an experiment on modification of a helical gear pair has been done, which showed that the calculated results agreed with experimental data and the carrying behaviour of gear transmission was improved considerably.

Key words Helical gears Flexibility Modification Finite element methods

OPTIMIZATION DESIGN OF WHOLE CONSTRUCTION OF MULTISTAGE DISK

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ABSTRACT

The optimization design of a whole construction of multistage disk, which is of great significance in practice, is the further development of optimization design of sin-

gle-stage disk configuration. The ways of auto-shape description, strength calculation of single-stage disk with finite-element method, optimization and coordination composition of multistage disk and configuration optimization of all disks, are taken to develop the software SODMROD. The calculation examples are provided. This paper also introduces the principles of shape description of disk section as well as deduction of some formulas and the formulas which are used in the deformation calculation between disk and drum.

Key words Multistage disk Structural design Optimization Finite element methods

STATE- OF- ART AND PROSPECTS OF TRANSONIC CENTRIFUGAL COMPRESSOR DEVELOPMENT

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ABSTRACT

A review on the methods for predicting internal flowfield and designing aerodynamic shape of transonic centrifugal compressor is given in this paper. In general, the development of the transonic centrifugal compressor lags behind that of transonic axial compressor. However, the transonic centrifugal compressor will be widely applied to powerplant of helicopters, the turbochargers of vehicles and compressors of petroleum-chemical industry etc. Thanks to an urgent need of engineering practice, it can be prophesied that transonic centrifugal compressor will make great progress within the coming several decades. At present, inviscid calculation method with a distributed loss model (or boundary layer calculation) is a main tool to predict or design the transonic centrifugal compressor. However, along with development of computer, 3D Navier-Stokes solver may be applied in engineering practice within the coming decade. In the inviscid calculation method, the S1 and S2 stream surface calculation method is the most important method at present. When the S1 and S2 method is used, the computer memory required is smaller and the CPU time consumed is shorter than 3D Navier-Stokes Solver. Of course, the S1 and S2 method is suitable only for non-separated flow condition at design point. As for design methods of the transonic centrifugal compressor, it is necessary to make full use of experience of axial compressor designing.

Key words Transonic compressors Centrifugal compressors Transonic flow

EXPERIMENTAL INVESTIGATION ON SURFACE STATIC PRESSURE DISTRIBUTIONS IN CURVED- BLADE COMPRESSOR CASCADE

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ABSTRACT

The static pressure distributions on endwalls and blade surfaces and the corresponding outlet flow for straight, leaned and curved blades of plane axial compressor cascades at 0° incidence were measured in detail. The experimental results show that C- shape static pressure distribution can be obtained on the blade surface of the curved blades along blade height. Blade leaning and curving can eliminate piling up of low energy fluid in the blade corner, cut down the endwall losses, retard corner stalling, and improve cascade aerodynamic characteristics.

Key words Blades Cascade tests Pressure distribution Static pressure