

二维粒子分离器的流场 及分离效率的数值模拟

西北工业大学 侯凌云* 严传俊

【摘要】 数值模拟了某型惯性粒子分离器(简称 IPS)的二维有粘轴对称流场分布、及各种不同尺寸砂粒的轨迹及分离效率,采用贴体坐标网格,并将多连通域转换成单连通域,在任意非正交曲线坐标系下求解 IPS 的分叉流动、粒子运动轨迹和分离效率。计算与实验结果吻合良好,表明:本文所采用的方法和编制的程序能反映粒子分离器的主要特征。

主题词: 分离器 流场 数值模拟

分类号: O242.4 O359

粒子分离器是用于安装在直升机发动机上,能有效分离砂粒。国外在 70 年代开始对粒子分离器进行设计、研制,国内对粒子分离器的分析计算尚属首次,目前对它的数值计算大多是针对二维无粘性流的情况^[1-3]。本文以文献[4]中有实验结果的一个惯性粒子分离器作为研究对象,针对二维有粘轴对称情况进行了流场分布及砂粒分离效率和运动轨迹的数值计算。

1 基本方程及计算方法

首先把任意形状的物理域变换成矩形的计算域,网格生成采用 Thompson J F 等人发展的椭圆型微分方程法生成,图 1 所示为用此法生成的粒子分离器的贴体网格,此网格在各壁面处加密,且在分流器唇口处网格与型面较吻合,这有利后面的流场计算。为了使流场计算在贴体坐标系下进行,必须把直角或圆柱坐标系下的控制方程转换成曲线坐标系 $\xi-\eta$ 中的形式。其曲线坐标系下二维轴对称湍流的基本微分方程可以用以下统一形式表示:

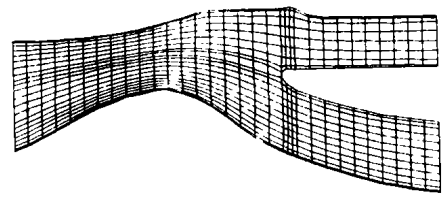


图 1 粒子分离器的贴体网格

$$\begin{aligned} & \frac{1}{J} \frac{\partial}{\partial \xi} (\rho U \Phi) + \frac{1}{J} \frac{\partial}{\partial \eta} (\rho V \Phi) \\ &= \frac{1}{J} \frac{\partial}{\partial \xi} \left[\frac{r \Gamma \Phi}{J} (\alpha \Phi - \beta \Phi) \right] + \frac{1}{J} \frac{\partial}{\partial \eta} \left[\frac{r \Gamma \Phi}{J} (-\beta \Phi + \gamma \Phi) \right] + S^\Phi(\xi, \eta) \cdot r \end{aligned} \quad (1)$$

其中: $U = r(ur\eta - vx\eta)$, $V = r(vx\xi - ur\xi)$, $\alpha = x^2\eta + r^2\eta$
 $\gamma = x^2\xi + r^2\xi$, $\beta = x\xi x\eta + r\xi r\eta$, $J = x\xi r\eta - x\eta r\xi$

在方程(1)中 Φ 取 1 时,表示连续方程;取 u, v 和 w 表示动量方程;取 k 和 ϵ 分别表示湍动能

方程和湍流耗散率方程。针对粒子分离器这一几何域,边界条件处理有其特殊性。根据入口流量和叶片旋角,给出入口轴向速度和切向速度,且假定是沿径向的等速度分布;对于出口截面上法向速度 u ,必须满足两个条件:(1)出口流量要满足计算区域的总体质量守恒;(2)主气流出口流量与清除流出口流量满足清除比(清除流流量与主气流流量之比)要求;在固壁上应用无滑移条件,在近壁节点上,采用曲线坐标系下的壁面函数法。采用有限容积法,将方程(1)在控制容积上积分并离散化,把离散化方程同上述边界条件结合起来,采用交错网格, SIMPLEC 算法求解整个流场。由于粒子分离器中分流器的存在,使 IPS 的流动呈分叉特性,由此形成了多连通域的结构,本文采用整个区域法将粒子分离器复杂多连通域转换成单连通域,将分流器结构视为流场中的堵块处理,这样处理程序收敛快,整个过程仅需 600 多次迭代。

由于粒子浓度属稀疏悬浮流,主要考虑气相场对粒子的作用,对气相场的求解采用欧拉坐标系,而对粒子的求解采用拉格朗日坐标系。在计算域中,曲线坐标系下粒子的运动方程和轨迹方程分别如下:

$$\begin{aligned} du_p/dt &= (u_g - u_p)/\tau_p, & dv_p/dt &= (v_g - v_p)/\tau_p + w_p^2/r_p \\ dw_p/dt &= (w_g - w_p)/\tau_p - v_p w_p/r_p \end{aligned} \quad (2)$$

式中 u_p, v_p 和 w_p 为粒子速度分量, u_g, v_g 和 w_g 为气体速度分量, τ_p 为驰豫时间。

$$d\xi_p/dt = (u_p r \eta - v_p x \eta)/J, \quad d\eta_p/dt = (v_p x \xi - u_p r \xi)/J, \quad r_p d\theta/dt = w_p \quad (3)$$

由于尘砂在粒子分离器中受到较大的离心力及型面的影响,粒子必将与粒子分离器的型面相碰撞,而后反弹。所以在研究粒子分离器中粒子流动时必须考虑碰撞的影响。粒子与固壁碰撞前后参数变化经验关系式为:

$$\begin{aligned} V_{n1}/V_{n2} &= 0.993 - 1.76\beta_1 + 1.56\beta_1^2 - 0.49\beta_1^3 \\ V_{t1}/V_{t2} &= 0.988 - 1.66\beta_1 + 2.11\beta_1^2 - 0.67\beta_1^3 \end{aligned} \quad (4)$$

式中 V_n 和 V_t 代表粒子的法向和切向速度,下标 1 和 2 分别代表碰撞前后状态。

分离效率是衡量一个 IPS 性能的重要指标,其定义为: $\eta_w = 1 - W_1/W_0$, 其中 W_1 为进入 IPS 的空气中所含砂尘的重量; W_0 为进入压气机的空气中所含砂尘的重量。

对于粒子运动方程(2)和轨迹方程(3),采用四阶 Runge-Kutta 法沿粒子轨迹积分求解。

2 计算结果及分析

粒子分离器的进口流量为 5.26 kg/s , 清除比为 16%, 旋流角为 36° ; 入口马赫数为 0.2, 气流密度为 1.211 kg/m^3 , 砂粒密度为 2650 kg/m^3 , 网格取为 33×22 , 砂粒在入口沿径向大致均匀分布,并分成 9 组。

图 2(图中—为内壁计算值,●为内壁实验值,---为外壁计算值,○为外壁实验值)示出内外壁静压沿几何形状轴向距离的变化,计算值与实验值^[4]吻合良好。从压力场图 3 可见:气流在主流路的速度大于清除流路;气流在分流器唇口处压力梯度变化大;粘性流场在 A 处附近有一回流区,尽管这一回流区不会对粒子分离器的分离效率带来很大的影响,但对总压损失有一定的影响。从粒子轨迹图 4 可见:当砂粒较小时,受气流作用大,尤其当砂粒为 $10 \mu\text{m}$ 时,由于气流的回流造成砂粒的轨迹也有逆流趋势,它们的分离主要是由于旋流的离心作用,但又由于向下径向速度的影响,致使有一部分砂粒进入主气流。当砂粒较大时,受气流作用小,与壁面的反复碰撞是它们分离的主要原因,这些碰撞导致粒子轨迹偏转而进入清除流路中。分离效率是随粒子尺寸的增大而增大。

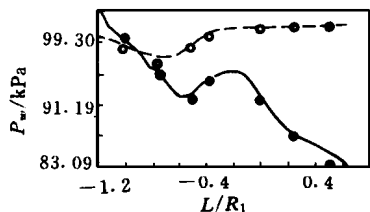


图 2 内外壁静压分布计算与实验值对比

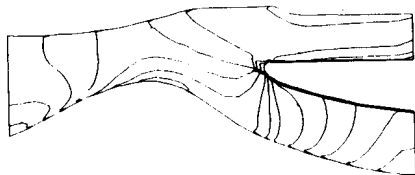


图 3 粒子分离器压力 P 等值线

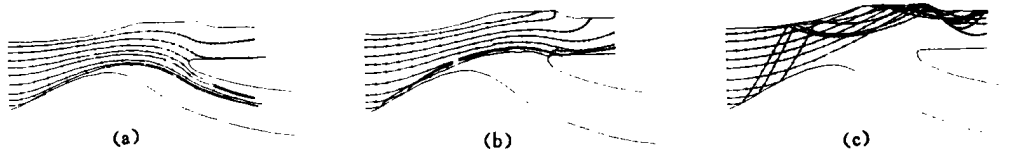


图 4 运动轨迹

本文所采用的方法和编制的程序对惯性粒子分离器的流场计算及粒子轨迹运动的计算是合理及成功的,能反映粒子分离器性能的主要特征,达到有效分离砂粒的目的。

致谢: 本研究得到中国航空工业总公司第 608 研究所资助,在研究过程中得到张乃光研究员的热心指导。

参 考 文 献

- 1 Vittal B V R, Tipton D L, Bennett W A. Development of Advanced Vaneless Inlet Particle Separator for Helicopter Engine. AIAA - 85- 1277, 1985
- 2 Breitman D S, Dueck E G, Habashi W G. Analysis of a Split- Flow Inertial Particle Separator by Finite Elements. J. Aircraft 1985, 22(2)
- 3 Hamed A, Jun Y D, Yeuan J J. Particle Dynamics Simulations in Inlet Separator with an Experimentally Based Bounce Model. J. Propulsion and Power, 1995, 11(2)
- 4 Robert J Duffy, Bernnard T Shattuck. Integral Engine Inlet Particle Separator. Volume II- Design Guide, USAAMRDL - TR- 75- 31B, 1975

(责任编辑 魏星禄)

index.

Key Words Liquid propellant rocket engines Fault detection Threshold value
Probability density function

APPLICATION OF ADAPTIVE VARIABLE NEURAL NETWORK TO AEROENGINE FAILURE DIAGNOSIS

Xie Shousheng and Fan Siqi

(*7th Dept. Northwestern Polytechnical University, Xi'an 710072*)

ABSTRACT A new adaptive variable neural network is developed according to the inner product feature of sample space. This method does not need to iterate learning. It features that its self-learning velocity is fast, accuracy is high, and it is able to change self-structure on work according to producing new sample. It has been applied to a type of aero-engine start system, its accuracy of failure diagnosis is prior to the original one, and the maintenance work is cut down. Moreover it has capability for real-time failure diagnosis, which opens up bright prospect for its propagation.

Key Words Adaptive control Failure diagnosis Neural network Aircraft engines

NEAR DEADBEAT CONTROL OF AN AEROENGINE SPEED SIMULATION SYSTEM

Sheng Wanxing and Dai Ruwei

(*Institute of Automation, Chinese Academy of Sciences, Beijing 100080*)

Wang Sun'an and Shi Weixiang

(*School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049*)

ABSTRACT The near deadbeat control design was applied to an aeroengine speed simulation system for flight handling simulation. High power demand of the aeroengine speed simulation system can be met by adopting a type of electrohydraulic pump controlled motor system. But the desired dynamic properties are difficultly obtained under the condition of large step input amplitude. According to the idea of deadbeat control, a method of quasi-deadbeat control design is proposed to overcome the difficulty. The experiments testified the effectiveness of the presented design.

Key Words Aircraft engine electrohydraulic control Servo system Simulator

NUMERICAL SIMULATION OF TWO-DIMENSIONAL FLOWFIELD IN PARTICLE SEPARATOR

Hou Lingyun and Yan Chuanjun

(*7th Dept. Northwestern Polytechnical University, Xi'an 710072*)

ABSTRACT The numerical simulation of the two-dimensional, viscous and axisymmetric flowfield and various diameter particle trajectories in a inertial Inlet Particle Separator (IPS) has been completed. For the complex boundaries, a grid system of the non-orthogonal body-fitted coordinates is generated, which is ideally suitable to this case; For the split flow, multiply connected regions are transferred to simple connected region. A SIMPLEC

algorithm for the full Navier–Stokes solver in generalized curvilinear coordinates is applied to calculate the viscous flow in the IPS. At last, the particle trajectories in the above viscous flowfield and separator efficiency are obtained. Good agreement between the experimental data and predicted results indicates that the presented procedure and its program contribute to development and design of future high performance inlet particle separator.

Key Words Flow fields Separators Numerical Simulation

AN IMPROVEMENT OF $k-\omega$ TURBULENT MODEL

Shen Huili

(7th Dept. Northwestern Polytechnical University, Xi'an 710072)

Zheng Xiaoqing and Liu Feng

(University of California U. S. A.)

ABSTRACT

The $k-\omega$ turbulence model for predicting turbulence transition at a local Reynolds number lower than that observed in experiments. Wilcox suggested an approach to predict transition through modifying the viscosity in the ω equation with five more closure coefficients, but the approach made the model too complicated. Here we introduce only one simple parameter to improve the model. An inequality is proposed to set a lower limit for the specific dissipation. In order to make the Navier–Stokes equations and $k-\omega$ equations strongly coupled, a staggered finite volume scheme for discretizing the N–S equations and the $k-\omega$ model equations has been developed. The algorithm was tested for a flat plate flow. Computational results show that the present improvement of the $k-\omega$ turbulence model to control the transition position is effective.

Key Words Turbulent flows Mathematical models Transition points Boundary layer

NUMERICAL SIMULATION OF NORMAL SHOCK WAVE/TURBULENT BOUNDARY LAYER INTERACTION WITH PASSIVE CAVITY

Liang Dewang

(2nd Dept. Nanjing University of Aeronautics and Astronautics, Nanjing 210016)

R. Bohning

(University of Karlsruhe Germany)

ABSTRACT

A full Navier–Stokes procedure, coupling with a Baldwin/Lomax turbulence model, is used to study the normal shock wave/turbulent boundary layer interaction with passive cavity. In addition, the ventilation velocity profile on the porous plate is calculated by an empirical model formulated from experiments. The total pressure and total temperature boundary conditions for inflow are given due to the existence of sonic section in the channel flow and the static pressure boundary condition for outflow is given as well. The comparison between numerical and experimental results shows that the presented procedure can predict the shape of the shock, the Mach number in front of the shock, the pressure ratio on the wall and position of the shock quite well.

Key Words Turbulent boundary layer Shock wave interference Control problems