

空天飞机复合循环推进系统新概念研究 ——组合发动机优化

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【摘要】 介绍一种用于空天飞机的组合发动机各工作模式切换的优化结果。优化过程中,在给定的飞行条件和选择的设计点参数情况下,对推进系统的安装推力、空天飞机的重量和性能作了详细的估算。

关键词: 空天飞机 组合发动机 优化 复合循环

1 前言

当前国外正研究的几种组合发动机,例如英国的 HOTOL,西德的 ATR,美国的 SCRAMJET 等都可用为空天飞机的动力装置^[1]。经分析研究,本文选定 SERJ 作为研究对象。这种组合发动机是双级入轨空天飞机的一种很好的候选动力方案。为了使发动机在各种飞行条件下发挥最佳性能,必须对其各子系统的工作配合进行优化研究,这是本文的研究目的。组合发动机 SERJ 由四个子系统组成,如图 1 所示:风扇、引射器、冲压和液化空气(LACE)子系统。气体发

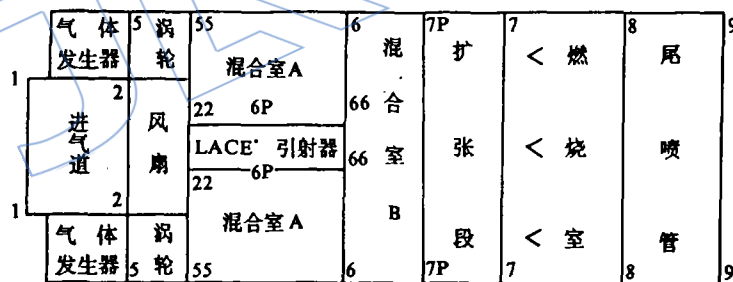


图 1 SERJ 组合发动机的流动模型

生器(燃烧液氢液氧)产生的燃气推动叶尖涡轮,带动风扇,流经涡轮后与风扇的气流在混合室内混合。从引射器(火箭群)出来的高温高压燃气对从混合器 A 流出的气流进行气动压缩,并在混合室 B 内掺混。混合室 B 流出的气流进入冲压燃烧室燃烧液氢。最后气流经尾喷管加速排出。所有的子系统都同时工作,称为 SERJ 模式,适用于低速飞行范围;关掉引射器子系统时,是风扇冲压(FRJ)模式;当飞行器加速至马赫数接近 3 时,关掉气体发生器,这便是冲压

(RJ)模式。在冲压模式时,如果再起引射器以增加推力就形成引射器压(ERJ)模式;在马赫数为 4.5~8.0 时,采用火箭(RK)工作模式,这时进气道关闭,冲压燃烧室不工作,只有引射器工作。

2 组合发动机性能和重量

组合发动机设计点的主要参数选择如下:飞行条件 $Ma_0=0$, $H=0$; 风扇增压比 1.8; 空气流量 400kg/s; 涡轮进口温度 1400K; 引射器压力 $1.03 \times 10^7 \text{N/m}^2$ 。

根据基本的质量守恒、能量守恒和机械能守恒方程对发动机设计和非设计点性能作了详细的估算^[2]。计算中采用了如下的假设:(1)发动机的调节规律为转速 $n=\text{常数}$, 涡轮前总温 $T_s=\text{常数}$, 风扇相对增压比 $=\text{常数}$;(2)气体发生器中为富氢燃烧,使出口气流温度在允许值范围;(3)进入混合器 A 的两股气流是平行的,进口截面上静压相等,混合室为等截面,出口截面上已混合均匀;(4)在引射器中液氢液氧按化学恰当比燃烧。温度超过 2500K 时,考虑热离解反应,按其最终的燃烧产物为 H_2 、 H_2O 、 O 、 H 、 OH 等应用化学平衡、质量平衡和能量平衡关系计算^[3];(5)混合室 B 扩张比为 2, 计算时也考虑高温区的热离解反应;(6)冲压燃烧室按化学恰当比燃烧,同时考虑热离解反应;(7)尾喷管喉部面积和出口面积可调,在各种飞行条件和循环模式下完全膨胀。考虑气流静温降低时的 O 、 H 、 OH 等还原;(8)液化空气子系统作为理想的换热器处理^[4]。

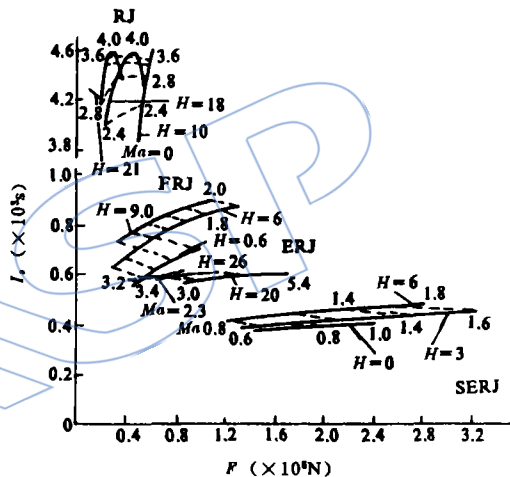


图 2 组合发动机推力 F 与比冲 I_s 的关系

图 2 表示计算结果,可以看出冲压工作模式的比冲 I_s 远大于其它工作模式的 I_s 。

在估算推进系统的安装推力时,考虑了进气道和尾喷管的内性能和外性能以及由发动机提取的功率等^[5]。

根据近似的公式估算了发动机部件的重量(kg),其结果如下:风扇组为 854,风扇机匣为 592,引射器为 1703,混合器、燃烧室为 1352,尾喷管为 1493,控制系统为 276,发动机总重为 6270;发动机推力为 $150.6 \times 10^3 \text{kg}$,推重比为 24.02。

3 空天机性能及重量估算

初步设想载机将轨道器加速到 $Ma_0=8$, $H=30\text{km}$,然后载机与轨道器分离,载机返回地面,轨道器继续加速到入轨速度。载机上安装 6 台 SERJ 组合发动机,轨道器上装有 LH2、LOX 火箭发动机。在载机飞行过程中动压限制条件为 $q=90\text{kPa}$,飞行轴向加速度限制小于 $3g$ 。

根据轨道远地点高度 h_1 ,火箭发动机停车高度 h_2 ,可确定轨道器入轨速度 V :

$$V = \{ [2/(h_2 + R) - 1/(h_1 + R)] \cdot g \cdot R \}^{1/2}$$

式中 g 为重力加速度, R 为地球半径。考虑到利用地球自转速度, 可确定火箭发动机停车时的速度 V_2 。

由轨道器与载机分离时的速度 V_1 , 火箭发动机停车时速度 V_2 , 按齐氏公式:

$$V_2 + \Delta V - V_1 = 9.81 \cdot I_s \cdot \ln(m_1/m_2)$$

可求出轨道器分离时相对于入轨时的相对质量 m_1/m_2 , 从而确定出轨道器的相对燃油量。最后根据选定的有效载荷, 参照现有飞行器各部分的相对重量系数的统计数据^[6]可确定出轨道器各部分结构、机载设备和燃油等的重量。类似地可计算出载机的各部分重量。

根据高空翼载估算公式^[7]确定出机翼面积后由有关运动方程积分可求得空天飞机飞行轨迹及其性能数据。

4 优化结果及分析

优化的目标函数是载机的燃料消耗量, 优化方法选用随机射线法^[8]。优化结果表示于图 3 和图 4 中。图 3 表示各参数(高度 H , 航程 S , 攻角 α , 航迹角 θ , 速度 V , 加速度 a)在空天飞机上升过程中随时间的变化曲线。

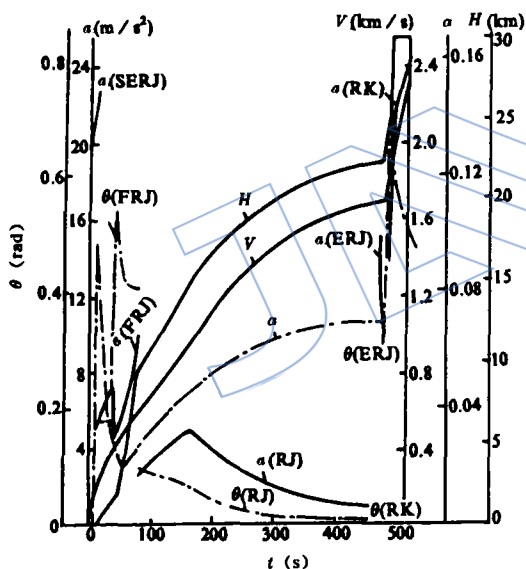


图 3 诸飞行参数随时间的变化

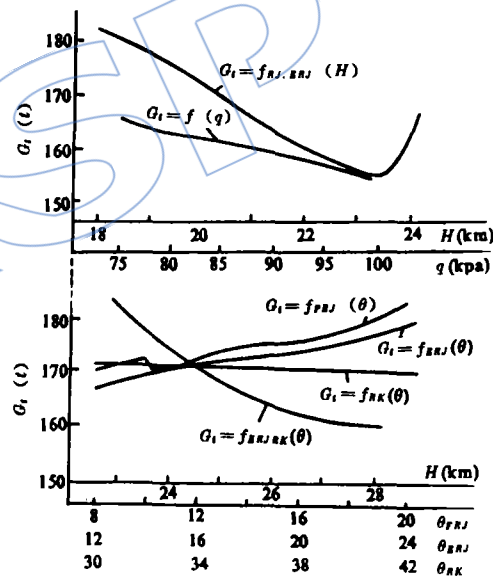


图 4 诸参数变化对载机燃料消耗的影响

对于所求得的最优参数, 固定其余各项, 令其一项变化, 可得在最优点附近的目标函数值特性^[9]。图 4 中的 $G_t = f_{FRJ}(\theta)$ 、 $G_t = f_{ERJ}(\theta)$ 和 $G_t = f(\theta)$ 、等曲线分别为 FRJ、ERJ 和 RK 工作模式下空天飞机航迹角变化对载机燃料消耗量的影响; $G_t = f_{RJ, ERJ}(H)$ 和 $G_t = f_{ERJ, RK}(H)$ 等曲线分别为燃料消耗量随组合发动机的 RJ 与 ERJ 模式, ERJ 和 RK 模式切换高度变化的曲线。从 $G_t = f_{ERJ, RK}(H)$ 曲线可见, 随着高度增加, 燃料消耗量急剧减小。但当 $H > 23.5$ 公里之后, 因空气过于稀薄, 推力减小过多, 燃料消耗量反而增加。 $G_t = f(q)$ 曲线为动压限的影响, 动压限越大则燃料消耗量越小, 因此在强度允许的范围内, 动压限应取较大的值。

本文还研究了载机与轨道器分离时飞行条件的影响。表 1 是三种情况结果的比较。

表 1 三种情况比较

分离时条件 $H(\text{km})/Ma$	24/5	27/6.5	30/8.0
起飞总重(t)	423	377	483
燃料消耗量(t)	228	201	278

可以看出在 $H=27\text{km}$, $Ma=6.5$ 条件下分离时,起飞总重和燃料消耗量比较低。其原因可解释如下:在载机与轨道器分离时,组合发动机的工作模式为火箭发动机。如果分离时的马赫数太大,当然用组合发动机的火箭模式使载机与轨道器一起加速不如用轨道器的火箭发动机使轨道器单独加速更为经济;但是如果分离的马赫数太小,则载机的一部分燃料转移到轨道器上,使轨道器的结构重量增加,从而使载机本身的结果重量亦增加。

5 结 论

(1)组合发动机采用变循环工作,其推力和比冲值分布范围广,适合作为空天飞机的动力装置。(2)本方案采用两级入轨,水平起落,可将 7 吨有效载荷送至 150~500 公里的运行轨道。(3)变化组合发动机各工作模式切换时的飞行条件,以载机燃料消耗量为目标函数可以获得最佳切换条件。(4)载机与轨道器的分离状态对空天飞机性能有很大影响,最佳分离马赫数约为 6~6.5。

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streamline curvature throughflow calculation method. The agreement of the calculation results with experimental data has been improved. It is believed that this simpler equation system can be applied to the flows not only in subsonic compressors, but also in transonic and supersonic compressors, provided that a more appropriate model is proposed for the coefficients.

A METHOD FOR OPTIMIZING THE MERIDIONAL PASSAGE IN A CENTRIFUGAL COMPRESSOR

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ABSTRACT A method for optimizing the meridional passage of the rotor in a centrifugal compressor has been developed according to the theory of $S1$ and $S2$ stream filaments. Two optimization principles are introduced. First, the gradient of static pressure in stream line direction should be minimized as it is mainly responsible for the boundary layer separation at the hub and shroud. Second, the gradient of static pressure from hub to shroud should be lessened as possible for it is generally considered as the major reason for triggering the second flow in the passage. According to these two principles, a reasonable criterion has been set up. In order to optimize meridional passage automatically through computer programming, two practical approaches have been provided. In one approach, the passage is modified again and again by using formulas derived from the continuity equation and thermodynamic relations. In the other, a series of quadratic curves are introduced to form a series of meridional passages. In both these approaches, it is necessary to predict the flow field by using "S2 inverse problem" computer code many times. Then, according to the above-mentioned criterion, the optimized meridional passage can be distinguished. Two numerical examples are given in this paper. Their results are obtained from the two approaches respectively. The comparison of the static pressure distributions at hub and shroud between the original and optimized passages indicates that this method obtains access to the expected results.

OPTIMIZATION OF A COMBINED-CYCLE PROPULSION SYSTEM FOR SPACE VEHICLE

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ABSTRACT This paper presents some results of optimization of operating modes transfer in a Supercharged Ejector Ramjet (SERJ) specified for first stage of a two-stage-to-orbit space vehicle. The SERJ consists of four subsystem; Fan, Ejector, Ramjet and Air liquefaction subsystem used as a heat exchanger. Three factors are considered for estimating propulsion system installed thrust; Internal and external performances of the inlet and the nozzle; power and air extractions from the engine. An objective of minimization is the minimum of the fuel consumption, which is attained by varying the transition conditions of different engine operation modes. Then the optimum transition conditions can be obtained between SERJ and fan ramjet modes, fan ramjet and ramjet modes, ramjet

and ejector ramjet modes, ejector ramjet and rocket modes.

VISCOUS FLOW FIELD PREDICTION IN AXISYMMETRIC PASSAGES

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ABSTRACT The viscous flow fields in the inflow axisymmetric passages of centrifugal compressors are predicted with vorticity-stream function (ω - ψ) method. The expressions of q - τ turbulence model equations in orthogonal curvilinear coordinate system are derived here, and they are used to predict the turbulent flow fields. The q - τ turbulence model has an advantage in capability of treating the boundary conditions. The unsteady terms are introduced in the ω -equation and q , τ equations, and the time-marching method is applied to solution of these equations. In the case of turbulent flow prediction the wall function is used in the near-wall region. Several numerical examples of laminar and turbulent flows in a 2D channel and axisymmetric passages with complex boundaries show that their solutions obtained with the present method is in good agreement with their exact solution or their experimental data.

DIGITAL SIMULATION OF TRANSONIC FLOW FIELDS IN A PLANAR NOZZLE

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Zen Jun (Gas Turbine Establishment)

ABSTRACT This paper presents a method for simulation of transonic flow fields in a planar nozzle. For this purpose, the Jumeson-type Runge-Kutta finite volume method is applied to solving Euler equation with the aid of local time stepping and implicit residuals averaging techniques. In such a manner the convergence rate is sped up in planar nozzle flow solution, so that the steady state can be obtained in less than a hundred iterations. An adaptive dissipation term is added to the equations to eliminate the fluctuation of the flow parameters and the vibrations in front of and behind the shock. The results of the calculations are in good agreement with the test data and the results of calculations with other numerical methods.

CALCULATION OF PRESSURE RATIO AT NOZZLE EXIT WITH SHOCK

Zen Jun and Zhao Jingyun

(Gas Turbine Establishment)

ABSTRACT A mathematical model of a axisymmetric convergent-divergent nozzle is set up by multivariant linear regression analysis method. The relationships of pressure ratio at nozzle exit with shock to four geometric parameters, i. e. area ratio, half-convergent angle, half-divergent angle and radius ratio of throat curvature to throat, are considered. The pressure ratio only depends on