

双轴涡喷发动机性能实时模拟简化模型*

西北工业大学 刘燕** 刘伟 陈辅群
沈阳航空发动机研究所 孙斌

【摘要】建立了能够实时模拟双轴涡喷发动机性能的数学模型。该实时模型包括:线性化的压气机特性模型、简化的涡轮特性以及非线性方程组的降维处理。在相同工况及进气条件下,分别用非实时模型和实时模型对某型双轴加力式涡喷发动机性能进行了模拟,并与试验结果进行了对比。结果表明,该模型很好地解决了提高运算速度与保证计算精度之间的矛盾,并且具有较高的收敛性。

主题词: 涡轮喷气发动机 性能分析 实时仿真 数学模型

分类号: V 235 111

1 前言

由于发动机全功能数字电调的发展,要求在很短的时间内对发动机的性能进行计算,以便满足控制系统的需要^[1]。因此迫切需要一种既能快速地、实时地模拟发动机稳、动态性能,又能保证一定精度的数学模型。本文在原非实时数学模型^[2]基础上,对试验压气机特性及涡轮特性进行了线性化处理,同时还将原非实时模型的六维非线性方程组降为四维,从而建立了简化的实时模型。该模型避免了插值计算发动机各部件的特性,大大提高了模型计算速度,大量地减少了模型在计算机内所占的内存,无需进行汇编处理便能在数字计算上实现不到 25ms 的快速发动机性能模拟。经过与试验结果和非实时模型计算结果相比较,证明本文提供的简化模型,无论是稳态性能还是动态响应都能很好的反映发动机的真实物理过程,既加快了运算速度,又保证了发动机的模拟精度,具有一定的使用价值。

2 压气机特性的线性化

为了尽可能减少模型计算时间,根据相似性准则,对压气机特性图进行了坐标变换,横坐标改为压气机出口的折合流量,纵坐标仍为压气机增压比。变换后的压气机特性图与传统的压气机特性图相比具有明显的优点,即每条等折合转速线近似为线性^[3]。利用此特点,经过一定的预先处理,可以完全不用查表插值计算压气机的特性,而用一些分段函数便能表示压气机的特性。下面介绍这种预处理方法。

首先利用最小二乘法拟合出每条等相对折合转速线的斜率与相对折合转速的关系

$$K_{\text{SLOPE}} = C_1 \bar{n}_{\text{cor}} + C_2 \quad (1)$$

再用最小二乘法拟合出所选基点的出口折合流量与相对折合转速的关系、基点的等熵温

升与相对折合转速的关系以及基点处效率的倒数与相对折合转速的关系

$$(M_{a, \text{cor}, \text{exit}})_{\text{基点}} = C_3 \overline{n_{\text{cor}}} + C_4 \overline{n_{\text{cor}}} + C_5 \quad (2)$$

$$A = [(\pi_{\text{基点}}^*) 0.2857 - 1] \times 10^5 / (\overline{n_{\text{cor}}})^2 = C_6 \overline{n_{\text{cor}}} + C_7 \quad (3)$$

$$B = [(T_{\text{exit}}^*/T_{\text{inlet}}^*)_{\text{基点}} - 1][(\pi_{\text{基点}}^*)^{0.2857} - 1] = C_8 \overline{n_{\text{cor}}} + C_9 \quad (4)$$

最后用最小二乘法拟合压气机特性上的任意点的温升比与基点的温升比之比与任意点的压比和基点的压比之比的关系

$$(T_{\text{exit}}^*/T_{\text{inlet}}^*) / (T_{\text{exit}}^*/T_{\text{inlet}}^*)_{\text{基点}} = C_{10} (\pi_{\text{基点}}^* / \pi_{\text{基点}}^*)^2 + C_{11} (\pi_{\text{基点}}^* / \pi_{\text{基点}}^* + C_{12}) \quad (5)$$

在已知压气机进口总温、总压的条件下, 取压气机相对折合转速及其出口折合流量为未知变量, 将(1)~(3)式代入下式可求出压气机增压比

$$\pi_{\text{基点}}^* = (\pi_{\text{基点}}^*)_{\text{基点}} \{1 - K_{\text{SLOPE}} \overline{m_{a, \text{cor}, \text{exit}}} / (m_{a, \text{cor}, \text{exit}})_{\text{基点}} - 1\} \quad (6)$$

则压气机出口压力 $P_{\text{exit}}^* = \pi_{\text{基点}}^* \cdot P_{\text{inlet}_0}^*$ 将求出的增压比及式(3)、(4)代入(5)式, 可求出压气机出口总温。用以上 6 式便可代替费时的压气机特性查表插值求压气机出口参数的工作。

3 涡轮特性的简化、发动机稳态及过渡态工作点的求法

在双轴涡轮喷发动机工作过程中, 两个转子之间相互气动作用的实质在于: 高压和低压涡轮的落压比以及它们的功率比都仅仅是发动机压缩过程总压比的函数^[4], 并且非实时模型的稳态、过渡态计算结果也证实了这一点, 所以本模型将高压、低压涡轮落压比和它们的功率比表示为发动机压缩过程总增压比的一维函数(见图 1)。取高压涡轮效率为常数, 以此代替费时的涡轮特性查表插值。

对双轴涡轮喷发动机, 在给定的调节规律低压转子转速等于常数 $n_L = \text{const}$ 的条件下, 用非实时模型进行稳态计算时取 6 个参数, 即高、低压压气机增压比、高压转子相对折合转速、涡轮前温度、

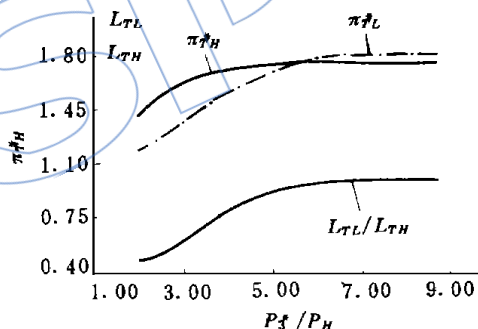


图 1 高低压涡轮落压比及功之比的变化

高低压涡轮进口流量相似参数等作为未知量, 过渡态计算时用低压转子相对折合转速代替涡轮前温度。根据流量连续方程、功率平衡方程、转速相等、压力平衡等, 建立 6 个共同工作方程。解它们构成的六维非线性方程组, 便得到发动机共同工作点参数。用本文的实时模型进行稳态、过渡态计算时取高、低压压气机出口折合流量、高压压气机相对折合转速、涡轮前温度(过渡态取低压转子相对折合转速)等 4 个参数作为未知量。建立 4 个共同工作方程, 解之得发动机共同工作参数。

4 模型仿真结果与分析

所有的数值模拟结果均在 BM-PC/386 微型计算机上进行, 该微机的主频 33 兆, 配以 80387 浮点运算器。在此外设条件下, 本文提供的模型每点计算时间小于 25ms。

图 2 为转速特性, 图中实线为非实时模型计算结果, 点划线为实时模型计算结果, 由图可见, 实时与非实时模型计算结果吻合较好, 最大误差约为 2.5%。

图 3 给出了在 $H = 0, M_a = 0$ 状态下, 发动机从慢车加速到最大状态, 然后下降至慢车的

动态响应曲线。实线为发动机实际试车曲线,点划线为非实时模型计算结果,虚线为实时模型计算结果。发动机动态模拟是在飞行状态和尾喷口面积给定的条件下,发动机的供油量作为时间的函数输入到实时模型中的。为了方便,实时模型中没有计入燃烧室的延迟和执行机构的延迟影响,也未计入部件的热惯性以及容积效应的影响。由图可见,在低转速、减速时误差较大,其主要原因是因为减速时供油量变化较快,而本模型又未考虑延迟及容积效应的影响。但误差仍然在工程精度限制以内(即小于 5%)。

图 4 给出了稳态及过渡态工作线在高、低压压气机特性图上的位置。高压压气机特性图上加速和减速状态的工作线位置,定性来看和单转子涡轮喷气发动机一样;而低压压气机则有本质的不同。这主要是由于两个转子的转速

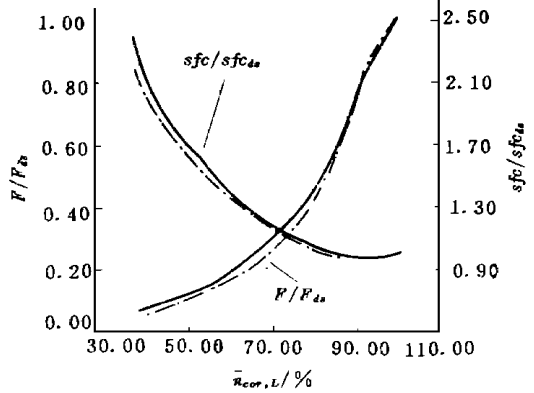


图2 双轴涡喷发动机的转速特性

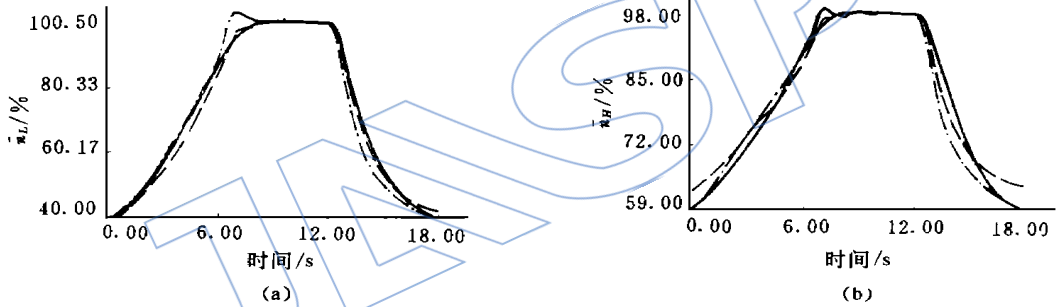


图3 发动机加、减速时(a)低压转子(b)高压转子相对转速的动态响应

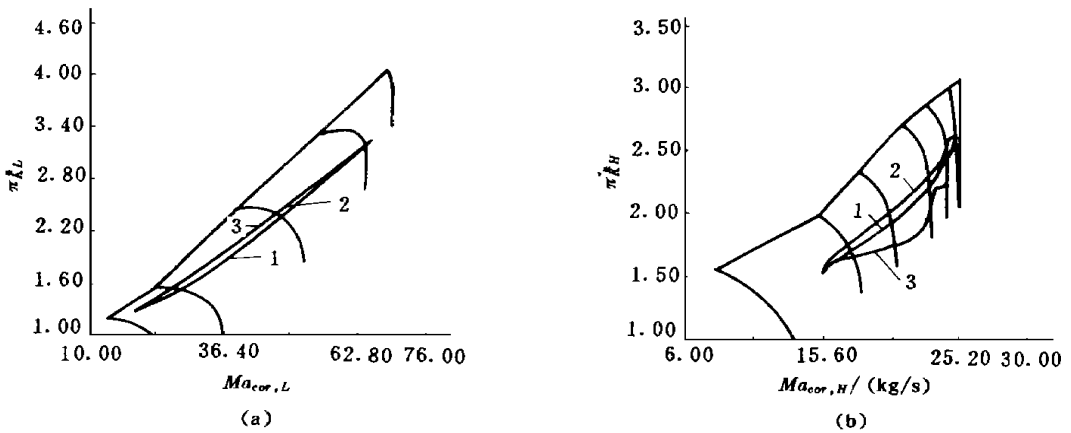


图4 (a)低压转子(b)高压转子工作状态(1—稳定工作状态, 2—加速装态, 3—减速状态)

不同所致,对于双轴涡喷发动机,随着低压转子折合转速的下降,转差率单调增加,两个转子间

的气动耦合引起转差率变化,这种气动耦合在过渡态也一直起作用。在加速和减速时,转差率随低压转子相对折合转速的变化差不多和稳定工作状态是一样的。但是,通常高压转子在慢车状态所具有的转速接近最大转速的程度比低压转子要大得多,并且高压转子的转动惯量比低压转子小些,因此在过渡工作状态时转差率按图 5 虚线所示那样变化。在加速过程中转差率比稳态工作值大,而减速时则小。结果加速时由于转差率的增大(即由于高压转子转速的增大),高压压气机进口的空气流量以及低压压气机出口的空气流量都比稳定状态时要大,亦即如图 4 所表示的那样,低压压气机特性曲线图上的工作点向右侧移动。相反,在减速时,如果高压压气机的转速降低得比较快,则降低转速对低压压气机中的气流起到了节流的作用,因此低压压气机的工作状态向稳定边界的方向移动。

由上可见,本文的计算结果是符合原理的,因而本文对发动机数学模型的线性化处理是成功的。此外,本文采用的计算方法及迭代方法具有较高的收敛性及运算速度,能够满足实时模拟发动机性能的需要。

参 考 文 献

- 1 Szuch J R. Application of Real- Time Engine Simulations to the Development of Propulsion System Controls AIAA, 1975: 75- 1176
- 2 James F Sellers, Carl J Daniele Dyngen a Program for Calculating Steady- State and Transient Performance of Turbojet and Turbofan Engines NASA TND- 7901, 1975
- 3 孙斌 双轴涡喷发动机性能计算机模拟 [学位论文] 西安: 西北工业大学航空动力与热力工程系, 1991
- 4 斯辽赫钦科 C M. 空气喷气发动机原理 北京: 国防工业出版社, 1982: 367

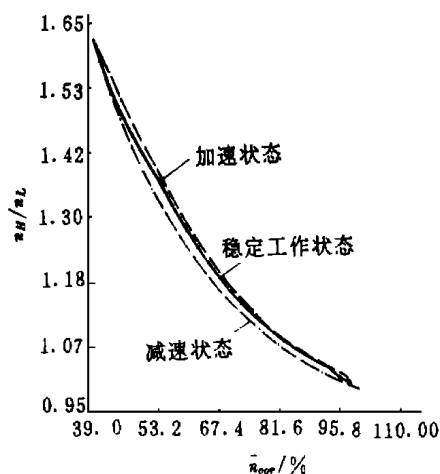


图 5 转子转差率随低压转子相对折合转速的变化

(责任编辑 魏星禄)

A MULTI- OPERATING POINTS GPA METHOD FOR ENGINE FAULT DIAGNOSIS

Chen Daguang, Han Fengxue, Tang Genglin

(4th Dept, Beijing University of Aeronautics and Astronautics, Beijing 100083)

ABSTRACT The feasibility of the multi- operating points gas path analysis (GPA) for engine fault diagnosis has been analyzed. The averaged error of estimation J is an effective criterion for determining the diagnosis accuracy. The recommended value of J has been given according to the numerical tests. It has been analyzed how the number of the operating points and the selection of the monitoring parameters affect the effectiveness of diagnosis. It is shown that the number of the necessary operating points can be significantly reduced and the diagnosis accuracy can be enhanced as the monitoring parameters are increased properly and selected correctly. Supplemental measurement of the pressure behind high pressure compressor and the pressure between high and low pressure turbines is a practicable measure for improving the diagnosis accuracy.

Key words Gas turbines Aircraft engines Fault diagnosis Gas path analysis

IMPACT OF VARIABLE GEOMETRY ADJUSTMENT ON TURBOFAN ENGINE PERFORMANCE

Zhu Zhili and Zhang Jing

(4th Dept, Beijing University of Aeronautics and Astronautics, Beijing 100083)

ABSTRACT The impact of variable geometry adjustment on performance of military turbofan engine with afterburner is analyzed and discussed. The results show as follows: During supersonic flight, increasing the nozzle throat area is an effective way to increase thrust of engine, and the higher the flight Mach number, the more remarkable the effectiveness; the nozzle throat area enlargement results in raising the surge margin of the fan effectively; the bypass ratio can be controlled by adjusting the ratio of inner and outer areas at mixer inlet, and enlarging inner area improves the performance of the engine with afterburner, but narrows the surge margin of the fan. The operating point of the fan will be optimized when the nozzle throat area and the area ratio of mixer inlet are regulated jointly and coordinately. It will be of benefit to the engine performance improvement that the pressure ratio of the fan and the mass flow increase simultaneously, while the efficiency and the surge margin of fan are kept up at a high level.

Key words Gas turbines Aircraft engines Performance analysis
Variable geometry adjustment

A REAL - TIME SIMULATION MODEL OF A TWO- SPOOL TURBOJET ENGINE

Liu Yan, Liu Wei, Chen Fuqun

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

Sun Bin (Shenyang Aeroengine Research Institute)

ABSTRACT A mathematical model for real-time simulation of two-spool turbojet engine has been established, which comprises a linearized compressor characteristics model, simplified turbine characteristics and the dimension-reducing method of non-linear equation set. Under the identical regime and inlet flow conditions, the performance of the two-spool turbojet engine was simulated respectively by real-time model and non-real-time model. The results of the simulations were compared with test data. Favorable results of the comparison give the validation of the fundamental hypothesis of this study. This model makes a very good compromise between computation

speed and accuracy, and has good convergence

Key words Turbojet engines Performance analysis Real-time simulation
Mathematical models

TRANSIENT PERFORMANCE SIMULATION OF A LARGE LIQUID ROCKET ENGINE UNDER FAULT CONDITIONS

Wu Jianjun, Zhang Yulin, Chen Qizhi

(1st Dept., National University of Defence Technology, Changshe 410078)

ABSTRACT A non-linear dynamic mathematical model for a large liquid rocket engine has been established, which comprises normal models and fault models based on large liquid rocket engine with turbo-pump system. The transient performance simulation has been performed under fault conditions according to jump input of various fault modes such as main valve fault, pipeline leakage, pipeline blockage, pump efficiency losses, turbine efficiency losses, which have occurred in previous hot-fire tests or will be possible to occur in future. Adaptive Runge-Kutta method is employed to simulate. The calculated results show that the established model is accurate and reasonable. The numerical method can simulate effectively the transient performance of the faults. Simulation results are also discussed and analysed in detail. The work lays the foundation for further study on choice of fault modes, fault detection and diagnosis based on the model.

Key words Liquid propellant rocket engines Dynamic models Mathematical models
Fault detection Fault diagnosis

SIMILARITY ANALYSIS AND NUMERICAL SOLUTION OF N-S EQUATIONS FOR LAMINAR FLOW IN A ROTOR-STATOR SYSTEM

Feng Qing and Liu Songling

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

Zhou Bin (Xi'an Oil College)

ABSTRACT The similarity analysis for the N-S equations and the boundary conditions of a rotor-stator system has been completed which shows that the flow field is dependent on five parameters such as inlet flow coefficient, rotational Reynolds number, gap ratio, shroud-clearance ratio and inlet diameter ratio. The numerical results for the laminar flow field in the system with an axial inflow and a radial outflow have been obtained by the SIMPLE method. It is shown that the gap ratio and the shroud have a great effect on the existence of the rotational core; and the core tends to take form and increase its rotational speed with decreasing the flow coefficient or with increasing the rotational Reynolds number. For the closed rotor-stator system the results are in good agreement with earlier work done by the other authors. Both the similarity analysis and numerical computation have testified the conclusion that the radial velocity is dominated by inertial terms and the tangential one is dominated by both inertial and viscous terms. The minimum of the flow coefficient required to prevent the ingress of gas into the rotor-stator cavity has been calculated, and its linear relation with the rotational Reynolds number has been found, which is consistent with the published experimental data very well.

Key words Wheels (Machine elements) Aircraft engines Air flow
Numerical solution of N-S equation