

并行处理双转子发动机实时仿真

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【摘要】 本文介绍在多处理机系统上实现双转子涡喷发动机的实时仿真。主控机为 PC286 微机;并行处理机由 4 个阵元机组成,阵元机选用微信号处理器 TMS32020; A/D、D/A 作为半实物仿真试验的用户接口。对发动机气动热力学模型算法进行“分割”,将 Jacobi 阵各列的元素分配在 4 个阵元机上并行计算。实时仿真支持软件管理各阵元机上程序模块的同步执行及数据通讯。本实时仿真器已用于发动机数字控制系统的半实物仿真试验。

关键词: 双转子涡喷发动机 实时仿真 并行处理

1 多处理机系统

并行处理发动机实时仿真的硬件,是由主控机和并行处理机组成的多处理机系统。并行处理机由 4 个阵元机构成。主控机通过总线驱动接口与并行处理机的总线控制器互连,管理阵元机的调度、主控机与阵元机的通讯。主控机为 PC286 微机。阵元机由 TMS32020 微信号处理器构成,采用定点运算,使用汇编语言编程,支持程序模块化,便于对模型算法和部件特性数据的调试和修改。在 PC 机上扩充了系统管理软件,使用户在 FORTRAN 和 80286 汇编语言环境下,能方便地使用并行处理机。模/数转换器(A/D)与数/模转换器(D/A),提供了在半实物仿真试验中使用的用户接口。

2 发动机模型的并行算法

气动热力学模型是用迭代方法求解发动机在“准平衡”概念下构造的非线性方程组

$$f_i(x_1, \cdots, x_n) = 0, \quad i = 1, \cdots, n$$

Newton-Raphson 迭代过程,预解向量 x 按下式刷新: $X^{k+1} = X^k - J_k^{-1} F_x^k$ 。其中: $X = [x_1, \cdots, x_n]^T$; $F_x = [f_1(X), \cdots, f_n(X)]^T$, 为残差向量; J^{-1} 为逆 Jacobi 阵, $J = F_x'$; k 表示迭代步。调用发动机气动热力学计算过程计算残差和 J 阵元素。双转子涡喷发动机动态过程计算时, $n=4$, 转数 N_L, N_H 通过轴上不平衡扭矩的积分来计算。

在多处理机系统上并行实现发动机模型的计算,需要“分割”模型算法。本文以 Jacobi 阵元素的计算为出发点来分割模型算法。 J 阵元素用后向差分来计算, i 行 j 列元素为:

$$\partial f_i(X) / \partial x_j \approx [f_i(X + \Delta X_j) - f_i(X)] / \Delta X_j \quad i = 1, \cdots, n; \quad j = 1, \cdots, n$$

其中 $\Delta X_j = [0 \cdots \Delta x_j \cdots 0]^T$ ($j = 1, \cdots, n$)。同列的 n 个元素可在同一次调用发动机气动热力学过程计算出来,各列元素的计算之间没有数值的依赖关系,即 $f_i(X + \Delta X_j)$ 的 n 列元素由 n 个处理机并行计算,程序的结构框图如图 1 所示。

在 4 个阵元机上并行计算 J 阵的 4 列元素, 赋初猜值, 计算残差和刷新猜值, 安排在其中的一个阵元机上, 帧周期时间由该阵元机的执行时间所决定。通过阵元机间的通讯, 实现各计算模块的数据传送。在迭代的最后一次调用气动热力学计算过程时, 计算转速和所需截面的静参数。主控机通过 A/D 采集主供油量 W_f 、加力供油量 W_{fa} 和喷嘴面积 A_s , 并传送给各阵元机, 并行处理机完成平衡计算后, 将转速 N_L 、 N_H 及所需截面参数回送主控机, 并通过 D/A 向控制系统输出。

3 发动机实时仿真支持软件

实时仿真支持软件是指能够使用户在多台处理机系统上, 实时(在线)运行发动机模型和管理用户接口的程序系统。非实时(离线)的支持软件, 用于试验前对仿真系统的准备, 实验后对记录数据的处理。仿真支持软件包含三方面的功能: 对发动机模型实时运行的支持、对用户接口的支持和对仿真试验数据记录的支持。仿真支持软件保证在 4 个阵元机上并行操作的发动机模型各程序模块的同步运行、数据通讯和软件进程的调度管理。A/D、D/A、图形显示、数据存贮、人/机交互等管理程序, 安排在由于通讯所分割开的时间间隔中执行。仿真时, “在线”显示动态工作点在高压压气机特性图上的位置; 试验后, 在压气机特性线上将动态过程复现出来。在 PC 机上运行的“在线”部份的支持软件, 执行时间必须与并行发动机模型程序的运行时间相匹配, 保证各程序进程的同步。

4 应用

并行处理双转子发动机实时仿真器已用于发动机/数字控制系统半实物仿真试验, 该试验

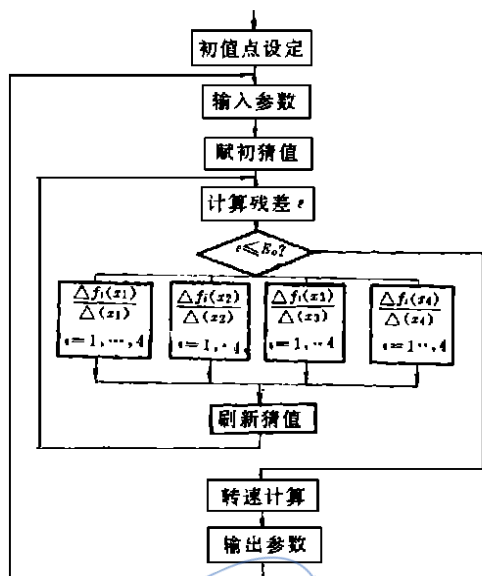


图1 发动机动态仿真并行计算程序框图

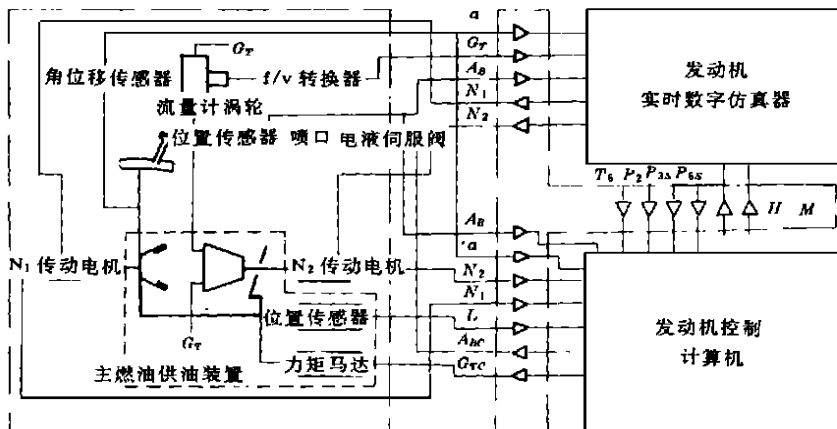


图2 主燃油系统半实物仿真示意图

系统如图 2 所示。发动机实时仿真器从控制系统输入供油量和喷口面积, 向试验器输出两个转子的转速, 向控制器输出涡轮后总温和压气机后总压。

用原型机械液压控制器进行半实物仿真, 检验本仿真器在闭环运行中稳态点输出参数的平均值及波动量, 在调节器自动工作转速以上的状态中, 供油有 3.5% 的波动量, 仿真器输出转速摆动量不超过 0.15%, 压气机总增压比波动不大于 0.35%, 涡轮后总温波动不大于 1.5%。加、减速过程($N_L = 0.35 \sim 0.95$)的仿真结果如图 3 所示。

在研制发动机数字控制系统的半实物仿真试验中, 对控制方案、参数、控制功能, 对控制器硬件、软件, 对传感器和执行部件等, 进行了大量的调试和评定工作, 对保证地面试车的安全、降低试验费用和缩短试车周期有重要作用。用试车记录的加、减速供油量和喷口面积输入仿真模型, 输出的两个转速与试车结果相差, 加速过程不大于 $\pm 1.8\%$, 减速过程不大于 $\pm 2.3\%$ 。本实时仿真器的帧周期时间, 非加力状态为 29.6 毫秒。

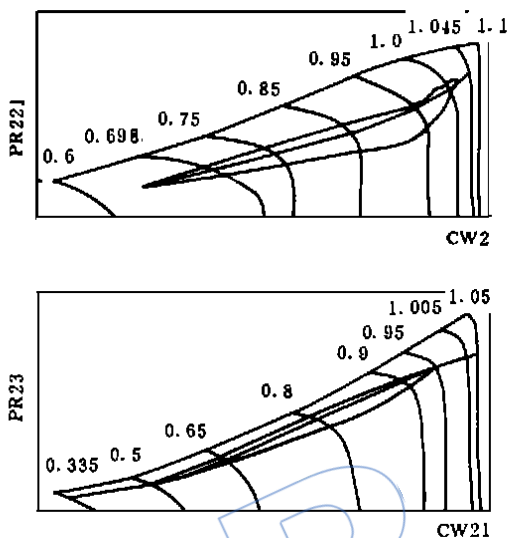


图 3 半实物仿真试验的加、减速过程

参 考 文 献

- 1 Szuch J R. Advancements in Real-Time Engine Simulation Technology. AIAA-82-1075, 1982
- 2 McLoughlin P W, et al. Parallel Processor Engine Model Program. NASA N84-19353, 1984
- 3 Roth S P, Celiberti L A. Micro-Computer/ Parallel Processing for Real-Time Testing of Gas Turbine Control Systems. AIAA-87-1926, 1987
- 4 Wood R A, Louton S E. Simulation Support Software in a Real-Time Environment at the U. S. Air Force Flight Test Center. Aerospace Simulation, Simulation Series, 16(2)

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paper. In addition, a brief analysis of the causes for initiation of this phenomenon was made on the basis of the experiments. Therefrom it is shown, that this phenomenon will cause flame periodical fluctuation.

AN EXPERIMENTAL STUDY ON FLUID FRICTION AND HEAT TRANSFER IN COMPLEX NONCIRCULAR PASSAGES

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ABSTRACT

Due to the effect of centrifugal force in an operating turbine, the passage between the tenon of blade root and the mortise of the disk is formed as complex noncircular flow passage. The characteristics of flow friction and heat transfer in this kind of noncircular passages are investigated experimentally. It is discovered that the "multiple flow states" occur in the noncircular passages and some special features exist in the flow friction and heat transfer characteristics. The criteria of the flow friction and heat transfer are obtained for this case.

LOADING MODELS FOR BIRD IMPACTING ON BLADES

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ABSTRACT

In order to predict the blade response to bird impact, it is necessary to establish the bird impact loading models at the first. For this purpose, the following research work has been completed: (1) Analyzing the physical process of the bird impact according to the theory of high-speed stroke dynamics, (2) accomplishing the loading experiments of the bird impact, and (3) studying the effect of the various factors of the bird impact loading on the blade response by means of computer numerical simulation. Based on the synthesis of the above research results, some methods and principles for the bird impact loading models are obtained. They are the method of determining the impulse and loading duration, the method for selecting the force-time function and the principles of determining the spatial factors of the loading including the load types, the loading location and the spatial distribution of the loads. These methods and principles are applicable to establishing the bird impact loading models.

REAL-TIME SIMULATION OF A TWO-SPOOL TURBOJET BY PARALLEL PROCESSING

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ABSTRACT

A real-time simulator of a two-spool turbojet is introduced, which is implemented with a parallel-processor/microcomputer system. A PC286 microcomputer is used as the host computer, and four TMS32020 digital signal processors are chosen as processing units of the parallel system. The A/D and D/A boards serve as the interfaces of the hardware-in-the-loop simulation of the engine control system. For the parallel processing, it is necessary to partition the aerothermodynamic model of the two-spool turbojet. The elements of Jacobian matrix of Newton-Raphson's iterative method are calculated parallelly in the 4 processing units. The whole real-time simulation was carried out under the control of the simulation support software, which guaranteed synchronous operation and communication between different processing units, A/D, D/A, the display, and the storage. The real-time engine simulator has been applied to the hardware-in-the-loop simulation for an engine digital control system. The simulation frame cycle time is 29.6 milliseconds.