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航空发动机 LPV 建模方法改进

李述清,张胜修,周志清,马昌兵
(第二炮兵工程学院 精确制导教研室,陕西 西安 710025)

摘 要: 针对航空发动机线性变参数(Linear Parameter Varying: LPV) 模型存在误差积累的问题,提出一种改进 LPV 模型。以某型涡扇发动机非线性模型为基础,建立以低压转子转速为调度变量的涡扇发动机 LPV 模型,在该模型上增加一个转速 - 供油量反馈,连同一个 PI 环节形成闭环回路,实现对 LPV 模型的改进。仿真结果表明: 改进 LVP 模型可以有效地克服 LPV 模型误差积累的缺陷,更真实地反映非线性模型的稳态和动态特性。

关 键 词: 航空发动机; 增益调度; 线性变参数模型; PID
中图分类号: V233.7 文献标识码: A

引 言

航空发动机是复杂的非线性系统。利用非线性数学模型对发动机的控制器进行设计,可以获得很高的控制精度,但由于该方法计算量大、算法复杂,使其在工程应用中受到一定的影响。因此,通常利用线性化方法建立航空发动机线性模型,再根据线性系统理论进行控制器设计[1~2]。发动机线性模型主要用于稳态控制分析中,对于偏离线性模型设计点较大的工况就不适合了。为适应发动机动态过程分析,文献[3~6]提出了通过线性模型建立发动机线性变参数模型的方法,发动机线性变参数模型得到迅速发展[7~10]。

文献[5~6]根据航空发动机非线性模型,采用内插或拟合方法求取线性状态空间模型系数矩阵,建立基于局部线性模型的涡扇发动机 LPV 模型,并在动态过程中得到应用。同时还指出,与非线性模型相比,LPV 模型存在一定的稳态误差: (1) 线性模型误差和线性模型系数拟合误差等; (2) 前一个线性模型的输出作为后一个线性模型的输入形成的误差。误差积累影响了 LPV 模型的精度。

为解决航空发动机线性变参数模型误差积累的问题,本研究提出改进 LPV 模型,即根据某型涡扇发动机非线性模型,建立以低压转子转速为调度变量的涡扇发动机 LPV 模型,在该模型上增加一个转速 - 供油量的反馈,连同 PI 环节形成闭环回路,实现对涡扇发动机 LPV 模型的改进。通过仿真验证改进 LPV 模型的有效性。

1 LPV 模型

对于所研究的某型涡扇发动机,只考虑两个独立转子部件为储能元件,可取系统状态变量 $x = [n_1, n_2]'$,n_1、n_2 为分别为低压、高压转子的相对转速(实际转速与设计转速的比值) ,第一输入为主燃室供油流量 $u = W_f$,输出为低压转子相对转速 $y = n_1$。于是,在平衡点($u_0 = W_{f0}$,$x_0 = [n_{10} \quad n_{20}]'$,$y_0 = n_{10}$) 附近的局部线性传递函数为:

$$G(s) = \frac{b_1 s + b_0}{s^2 + a_1 s + a_0} \tag{1}$$

发动机低压转子相对转速 n_1 是表征发动机工作状态、实施发动机控制的重要参数,选 n_1 作为发动机 LPV 模型调度变量 ρ,即 $\rho = n_1$。

根据 LPV 建模方法,基于发动机线性传递函数(式(1)) ,采用内插或拟合方法求取系数[5~6],得到涡扇发动机传递函数:

$$G(s;\rho) = \frac{b_1(\rho) s + b_0(\rho)}{s^2 + a_1(\rho) s + a_0(\rho)} \tag{2}$$

其中,系数 $b_1(\rho)$、$b_0(\rho)$、$a_1(\rho)$、$a_0(\rho)$ 是关于调度变量 $\rho = n_1$ 的拟合或插值关系式。

在确定出系数与调度变量的拟合或插值关系后,即可建立发动机 LPV 模型,如图 1 所示。

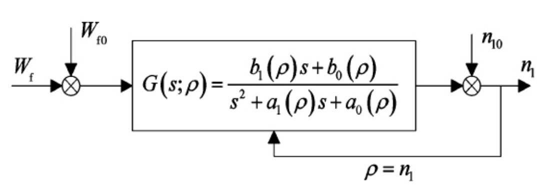

图 1 涡扇发动机的 LPV 模型

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作者简介: 李述清(1981 -) ,男,湖南怀化人,第二炮兵工程学院博士研究生.

2　改进 LPV 模型

根据反馈控制思想，提出改进 LPV 模型，如图 2 所示。

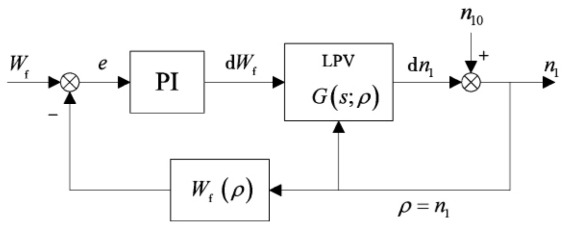

图 2　涡扇发动机改进 LPV 模型

改进 LPV 模型的传递函数 $G(s;\rho)$ 与原 LPV 模型一致，燃油流量 $W_f(\rho)$ 可通过调度变量 $\rho = n_1$ 拟合或插值计算，将 $W_f(\rho)$ 环节作为反馈，与实际燃油流量 W_f 进行比较，通过 PI 环节实现燃油量偏差 $G(s;\rho)$ 对输出的调节。

采用二次多项式估算燃油流量 $W_f(\rho)$ 的拟合形式，拟合效果如图 3 所示。拟合精度较高，这为涡扇发动机改进 LPV 模型精度提供了保障。

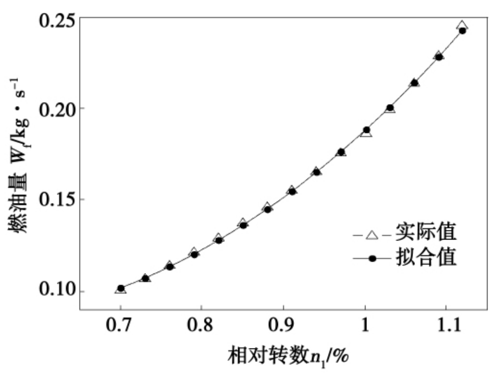

图 3　燃油量 W_f 与低压转子相对转速 n_1 的拟合效果

根据相对转速为 0.9 时涡扇发动机线性模型，选取 PI 环节：$1.05 + 1.6882/s$。

3　仿真分析

为了检验改进 LPV 模型的有效性，对发动机从低转速工况到最大转速工况的阶梯加速过程，分别利用发动机非线性模型、LPV 模型及改进 LPV 模型进行开环仿真，仿真结果比较如图 4 所示。

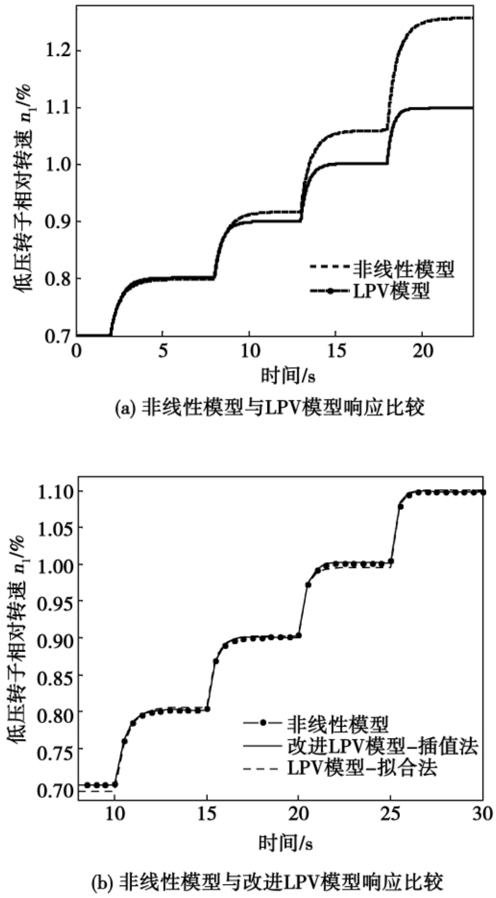

图 4　三种模型的仿真比较

一方面，原 LPV 模型的误差积累很严重，如图 4(a) 所示，这使得原 LPV 模型在处理发动机宽工况仿真情形中就不适用了，这也正是原 LPV 模型的局限。另一方面，如图 4(b) 所示，改进 LPV 模型仿真得到满意效果：对于估算燃油流量 $W_f(\rho)$ 无论采用拟合法或插值法，改进 LPV 模型的稳态精度都很高，而且与非线性模型的动态响应品质保持一致。可见，改进 LPV 模型保证了精度，且保持了原 LPV 模型形式的简洁性和解算的快速性，这为基于 LPV 模型的涡扇发动机控制器设计与分析带来极大方便。

4　结　论

针对航空发动机 LPV 模型存在稳态误差积累的缺陷，提出了改进 LPV 模型。根据某型涡扇发动机非线性模型，建立以低压转子转速为调度变量的涡扇发动机 LPV 模型，在该模型的基础上增加一个

转速 – 供油量的反馈，连同 PI 环节形成闭环回路，得到对原 LPV 模型的改进。对发动机从慢车状态到最大状态的阶梯加速过程进行仿真，结果表明：改进 LPV 模型继承了原 LPV 模型形式简单、解算快速的特点，同时克服了原 LPV 模型误差有积累、稳态精度不高的缺陷，能够与非线性模型的动态响应品质保持一致。

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新技术、新设计

用于美国海军 DDG51 计划的 LM2500 燃气轮机

据《Gas Turbine World》2010 年 7 ~ 8 月号报道，GE Marine 最近宣布，它的 LM2500 船舶燃气轮机将用于驱动美国海军 Light 2A 阿里 · 伯克级驱逐舰。GE 已接到了计划新制造的 9 艘 Flight 2A 中最初 3 艘舰的订单。

建造这些新的宙斯盾驱逐舰正是美国海军 DDG51 计划的一部分。DDG51 计划包括已交付的 57 艘该级驱逐舰，另外增加的 5 艘该级舰正在建造中，它们全部是由 GELM2500 燃气轮机驱动。

LM2500 燃气轮机安装和拆除之间的时间约为 23 000 h，它相当于使用约 17 年。

用于 DDG51 计划的这些新驱逐舰正在美国缅因州巴思布的巴思钢铁厂和密西西比州帕斯卡古拉布的 Northrop Grumman Shipbuilding 造船厂建造。

GE 将为每艘阿里 · 伯克级宙斯盾驱逐舰提供 4 套 LM2500 燃气轮机成套装置。装置的供货范围包括 LM2500、底座和箱装体、单冷却器润滑油储存和调节组件。

用于最初 3 艘新舰的 LM2500 燃气轮机成套装置预期于 2011 年开始交付给造船厂，并于 2013 年完成交付。

（吉桂明　摘译）

内陆核电站汽轮机选型及冷端优化 = Type Selection and Cold-end Optimization of a Steam Turbine in an Inland Nuclear Power Plant [刊，汉] LUO Bi-xiong, CHEN Juan, ZHU Guang-yu, et al (Guangdong Provincial Electric Power Design and Research Institute, Guangzhou, China, Post Code: 510663) // Journal of Engineering for Thermal Energy & Power. – 2011, 26(2). – 158 ~ 161

Cold-end optimization of power plants has its intentions to secure a maximal profit in the whole service life of the units. The cost and income should be taken into account comprehensively. The configuration of steam turbines, condensers, cooling towers and related systems exercise an influence on the cost. Different steam turbine exhaust areas, condenser heat exchange surface areas and cooling tower surface areas correspond to different annual power generation capacities. Only a properly designed back-pressure can guarantee the units to obtain a maximal benefit in the whole service life of a power plant. According to the plant site conditions of an inland nuclear power plant, through a calculation of exhaust areas of steam turbines, selection of heat exchange surface areas of condensers and design of cooling towers and circulating water systems, the types of the steam turbines were chosen and a comprehensively optimized design of the cold end was performed of the above-mentioned nuclear power plant. The optimum design back-pressure of the condensers and the cooling tower area were finalized to guarantee the units to obtain an optimum benefit in the calculated service life period. The foregoing can offer reference for design of power plants of the same type. **Key words:** nuclear power plant, type selection of steam turbines, cold-end optimization

压气机不同运行工况下湿压缩性能分析 = Analysis of the Wet Compression Performance of a Compressor Under Different Operating Conditions [刊，汉] ZHENG Hong-tao, CHEN Pei (College of Power and Energy Engineering, Harbin Engineering University, Harbin, China, Post Code: 150001) //Journal of Engineering for Thermal Energy & Power. – 2011, 26(2). – 162 ~ 167

The wet compression technology can effectively enhance the power output of a gas turbine and lower the degree of dependence of the gas turbine on the atmospheric environment. The factors the technology influences the compressor are very intricate and the operating conditions of the compressor have a very big influence on the wet compression effectiveness. By employing software CFX, a three-dimensional numerical simulation was performed of the dry and wet compression process of a three-stage axial compressor under different operating conditions. The research results show that under the condition of the pressure ratio keeping constant, the mass flow rate will increase at a high speed and decrease at a low speed at the boundary where the compressor approximates to its stall. Under the condition of the rotating speed keeping unchanged, both pressure ratio and mass flow rate of the compressor will tend to decrease. The lower the pressure ratio, more conspicuously the mass flow rate of the compressor will decrease. After the compressor has been humidified, the higher the rotating speed of the compressor, the more it approximates to its stall point and the more the total temperature will decrease. During the wet compression, the water drops are vaporized into steam, resulting in an increase of the total power consumed by the compression to a relatively big extent. All the calculation cases have increased by more than 500 kW at various operating points. After the compressor has been humidified, whether the worst separation point on the back of the rotor blades at their tips can be improved is related to the concrete operating point and there exists certainly a critical operating point. For the cases calculated by the authors, the above-cited critical point is assessed at about 90% of the rated speed. **Key words:** gas turbine, compressor, wet compression performance, off-design operating condition, numerical simulation

航空发动机 LPV 建模方法改进 = Improvement of the LPV (Linear Parameter Varying) Method for Modeling an Aeroengine [刊，汉] LI Shu-qing, ZHANG Sheng-xiu, ZHOU Zhi-qing, et al (Precision Control and

Guide Teaching and Research Section, No. 2 Artillery Engineering College, Xi'an, China, Post Code: 710025) //
Journal of Engineering for Thermal Energy & Power. – 2011, 26(2). –168 ~ 170

In the light of an error accumulation problem of the LPV (linear parameter varying) model, an improved LPV model was put forward. On the basis of a nonlinear model for a turbofan engine, a LPV model for the turbofan engine was established with its LP rotor rotating speed serving as a scheduling variable. A rotating speed-oil supply quantity feedback was added to the model in question. Together with a PI link, a closed loop circuit was formed, achieving an improvement of the LPV model. The simulation results show that the improved LPV model in question can effectively overcome the error accumulation defect of the LPV model, thus more realistically reflecting the steady and dynamic state characteristics of nonlinear models. **Key words:** aeroengine, gain scheduling, linear parameter varying model, PID (proportional, integral and differential)

双压凝汽器闭式循环水系统的最优运行方式 = Optimal Operation Mode of a Dual-pressure Condenser Closed Type Circulating Water System [刊,汉] ZENG De-liang, WANG Wei, LIU Ji-zhen (College of Control and Computer Engineering, North China University of Electric Power, Beijing, China, Post Code: 102206), ZHANG Zhi-gang (Datang International Tianjin Panshan Power Plant, Tianjin, China, Post Code: 301900) // Journal of Engineering for Thermal Energy & Power. – 2011, 26(2). –171 ~ 175

Circulating water inlet temperature is regarded as an important parameter for determining the optimal operation mode of a circulating water pump. For an open type circulating water system, the circulating water inlet temperature represents the ambient temperature. For a closed type one, however, it denotes the cooling tower outlet water temperature. With a counterflow type cooling tower serving as an object of study, in combination with the heat balance calculation formulae for a cooling tower and by adopting an iterative calculation method, the tower outlet water temperatures under different operation modes were determined. In the meantime, a soft method for measuring the tower ingoing air speed was presented. In the earlier literatures, however, the tower ingoing air speed was invariably obtained by an aerodynamic calculation. The problem concerning the multiple solutions to the nonlinear equation in the calculation of the tower outgoing water temperature and ingoing air speed was expounded. A real solution coincident with the physical meaning was finalized. At last, the solution such obtained was applied in the dual-pressure condenser. The optimal operation mode obtained therefrom for the circulating water pumps can serve as a guide for on-site operations. **Key words:** tower ingoing air speed, tower outgoing water temperature, dual-pressure condenser, optimal operation

CO_2 跨临界双级压缩带回热器与不带回热器循环分析 = Analysis of a CO_2 Trans-critical Dual-stage Compression Cycle With and Without a Recuperator [刊,汉] WANG Hong-li, TIAN Jing-rui (College of Metallurgy and Energy Source, Hebei United University, Tangshan, China, Post Code: 063009), MA Yi-tai (Thermal Energy Research Institute, Tianjin University, Tianjin, China, Post Code: 300072) // Journal of Engineering for Thermal Energy & Power. – 2011, 26(2). –176 ~ 180

To address the ODP (Ozone Depletion Potential) and GWP (Global Warming Potential) problems arisen from freon refrigeration coolant, mathematical models were established for CO_2 trans-critical dual-stage compression cycle with a recuperator (TSCV + TGC + IHX) and without a recuperator (TSCV + TGC) by employing a thermodynamic method. In addition, based on Visual Basic program, a platform for analyzing the performance of both cycles was developed. It has been found that under the identical contrast conditions, the average performance of TSCV + TGC