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GT25000 燃机试验工艺基架动态特性研究

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摘　要: 采用有限元法及子结构技术, 建立了 GT25000 燃气轮机试验工艺基架结构系统的动力学模型, 详细计算了结构系统的固有特性及动态响应, 并讨论了阻尼和减振器对振动的影响。结果分析表明, 工艺基架结构有较好的动态特性, 其设计是合理的。

关　键　词: 燃机试验; 工艺基架; 子结构; 固有频率; 动态响应

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1　概述

随着燃气轮机技术的不断发展, 燃气轮机的振动问题日益被重视起来。GT25000 燃气轮机是从国外引进的工业和船用燃气轮机, 需对其进行陆上性能试验。为了保证试验工作的顺利进行, 其工艺基架的设计应满足规定的振动要求。因此, 对工艺基架结构进行动力分析, 主要有两个目的: 一是校核结构设计是否合理, 即能否避开与设备产生有害振动; 二是为试验提供一些有价值的计算数据。

本文采用有限元法及子结构技术, 建立了 GT25000 燃气轮机试验工艺基架结构系统的力学模型, 详细计算了结构系统的固有特性及动态响应, 讨论了系统阻尼和机组减振器对振动的影响。本文得到的一些结论, 可供有关设计人员和试验人员参考。

2　力学模型

GT25000 燃气轮机单机性能试验的主设备有燃气轮机和水力测功器。燃气轮机所做的功, 经其动力涡轮输出, 由水力测功器消耗。燃气轮机和水力测功器分别安装在各自的工艺基架上, 工艺基架的地脚螺栓与基础平台固定。燃气轮机的工艺基架结构较复杂, 它由排气管支架、主机架、前底架、后底架四个结构组成。

2.1　子结构划分

将燃机机组划分为发动机和排气管两个子结构, 与工艺基架相比其刚度不算很大。水力测功器简化为集中质量, 作用在测功器底架上。基础平台是一个长方形的钢筋混凝土结构, 划分为板壳单元, 而支撑它的地基简化为无质量的弹簧。排气管支架、主机架、前底架、后底架作为子结构, 整个结构共划分 8 个子结构和 1 个母结构, 如图 1 所示。整个结构系统共有板壳单元 2 025 个, 梁单元 482 个, 节点数 2 531 个, 自由度数近 13 000 个。

2.2　减振器刚度等效

GT25000 燃机机组共有 20 个减振器, 它的三个主刚度方向与总体坐标轴方向成某一夹角。根据能量守衡原理, 将减振器主刚度转换到总体坐标系中。最后将减振器简化为梁单元, 其刚度用梁的材料常数和截面参数来等效。

2.3　动态载荷及阻尼

动态载荷由燃气轮机动力涡轮转子和水力测功器转子的动不平衡力产生。为保守起见, 假设水力测功器的动载幅值为设备重量的 10%, 而燃机机组的动载大小为设备重量的 20%, 如表 1 所示, 列出了 4 种典型的动态载荷, 其中的阻尼假定为比例阻尼, 取 $\xi = 0.05 \sim 0.15$。

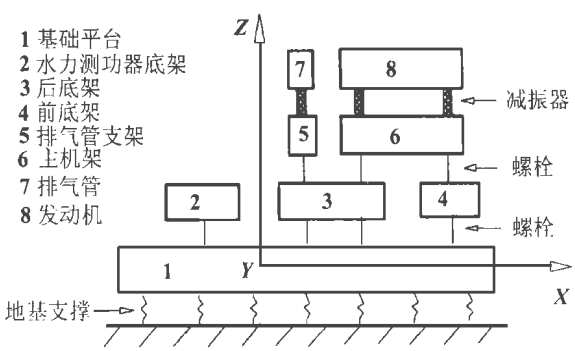

图 1　结构系统的力学模型

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表 1 动态载荷工况

工况	振动来源	激励方向	激振波形	减振器	阻尼
1	燃机机组	Z 向或 Y 向	正弦	不安装	无
2	燃机机组	Z 向或 Y 向	正弦	安装	无
3	燃机机组	Z 向或 Y 向	正弦	安装	有
4	燃机, 测功器	Z 向和 Y 向	正弦	安装	有

3 计算方法

采用通用程序 SAP84 进行计算。它的子结构功能是以“静力凝聚”原理为基础来设计的, 是一种准确的动力子结构算法(详见文献[3])。

4 结果分析

4.1 固有特性分析

4.1.1 对工艺基架各个结构单独进行频率计算(此时不计设备质量), 假设联接螺栓处为固支, 结果表明: 各结构的第一阶频率都在 110 Hz 以上, 大于机组工作频率的两倍。

4.1.2 考虑水力测功器的质量, 测功器底架的第一阶频率降至 35 Hz。考虑燃机机组(装减振器)的质量, 其前、后底架的地脚螺栓固支, 则其工艺基架结构的第一阶固有频率仅为 8 Hz。

4.1.3 整个结构系统的前 20 阶频率见表 2。考虑机组装减振器和不装减振器两种情况, 可见减振器的刚度对系统的固有特性有较大的影响。对于有减振器的情况, 前 20 阶频率值都在机组共振区以下。前 4 阶振型都是减振器在振动, 第 5 ~ 10 阶基本上是地基支撑弹簧的振型, 从第 11 阶起, 工艺基架各结构才显出自己的振型。而且发现, 减振器、地基弹簧及工艺基架三者之间并无明显的耦合振动。限于篇幅, 结构的振型图从略。

表 2 系统的前 20 阶固有频率 Hz

阶次	有减振器	无减振器	阶次	有减振器	无减振器
1	7.97	13.48	11	17.70	34.07
2	9.57	13.51	12	21.31	34.94
3	12.22	13.94	13	22.62	36.07
4	12.28	14.37	14	25.81	41.09
5	13.43	16.17	15	25.93	42.98
6	13.78	22.95	16	27.33	43.73
7	13.91	26.58	17	31.52	45.30
8	14.12	30.95	18	33.83	45.98
9	16.10	33.28	19	34.83	50.56
10	16.22	36.64	20	35.89	53.41

4.2 动态响应分析

我们求得了各动载工况下任一时刻的动态响应(包括位移、速度、加速度)。表 3 列出了各结构动态响应的最大合成值。

表 3 各结构动态响应的最大合成值

子结构	载荷工况	1		2		3		4
名 称	激励方向	Z 向	Y 向	Z 向	Y 向	Z 向	Y 向	Z+Y
基础	位移/μm	4.76	5.49	6.94	4.36	3.71	2.61	16.8
平台	速度/ mm·s^{-1}	1.19	1.33	1.11	0.45	0.63	0.23	3.01
测功器	位移/μm	2.70	4.00	4.43	2.94	2.52	1.74	17.10
底架	速度/ mm·s^{-1}	0.71	0.92	0.59	0.37	0.40	0.18	4.20
后底架	位移/μm	3.48	36.1	10.1	5.98	9.37	5.50	16.7
	速度/ mm·s^{-1}	0.77	12.3	2.04	0.88	1.92	0.76	3.04
前底架	位移/μm	4.09	45.0	4.65	8.77	3.35	8.05	15.4
	速度/ mm·s^{-1}	0.97	14.0	0.71	1.29	0.54	1.12	2.10
排气管	位移/μm	3.51	37.8	3.36	4.16	2.32	3.16	11.2
支架	速度/ mm·s^{-1}	0.79	9.84	0.49	0.53	0.36	0.44	1.93
主机架	位移/μm	3.77	39.1	11.2	8.36	10.4	7.68	19.0
	速度/ mm·s^{-1}	0.86	12.2	2.34	1.22	2.20	1.06	3.31
排气管	位移/μm	4.17	48.4	7.50	9.69	4.59	5.19	15.0
	速度/ mm·s^{-1}	0.93	13.0	1.09	0.61	0.60	0.37	1.88
发动机	位移/μm	4.91	127.5	59.9	88.9	55.6	81.5	94.4
	速度/ mm·s^{-1}	1.33	39.3	14.3	13.2	13.3	11.4	14.6

4.2.1 观察表 3 中的第 1 种工况(即无减振器情况), 发动机以同样大小的载荷作用于 Z 向或 Y 向, 所产生的响应差别很大。对于主机架、前后底架, Y 向激励产生的响应比 X 向激励引起的响应要大 10 倍以上。而对于产生激励的发动机本身, Y 向作用力引起的响应比 X 向作用力产生的响应要高出 25 倍以上。可见, 不装减振器, 发动机 Z 方向振动很小, 但无法避免 Y 向激烈振动。

4.2.2 对于有减振器的情况(工况 2 和 3), 发动机激励引起发动机本身的响应最大, 而工艺基架各结构的响应很小, 至少差 5 倍以上。这说明减振器起到减振作用。比如, 第 2 工况 Y 向作用, 主机架最大位移响应为 8.4 μm, 而发动机最大位移响应为 88.9 μm, 这说明发动机传递的振动已被减振器吸收了 90%, 因而对主机架仅有 10% 的影响。

4.2.3 当无减振器时(工况 1), Y 向作用力产生的响应总比 X 向作用力产生的响应大, 但对于有减振器的情形(工况 2、3) 并非如此。比如, 后底架振动以 Z 向激励为大, 相反, 前底架的振动以 Z 向激励为小。这可能与减振器对 Y 向或 Z 向振动的减振效果有关。

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的目的。船体、钝体等都是滞止浓缩过程和弥散过程在实践中的典型应用。

值得指出的是，由于一部分颗粒积聚在挡板表面上，使得后来的颗粒不是直接撞击到挡板上，而是通过与这层颗粒垫进行碰撞而滞止，降低了挡板受到的磨损和冲击，延长了挡板的使用寿命。目前国外已投运的用挡板作非流线型体的煤粉燃烧器的运行实践表明[4]，挡板在受到连续 20 000 小时的颗粒撞击后，几何尺寸改变很小。

5 结论

(1) 颗粒的滞止浓缩过程和弥散过程是浓缩煤粉燃烧技术的基础。

(2) 挡板可以使颗粒在其表面及边缘附近颗粒浓度急剧增加。

(3) 挡板滞止浓缩效应所能维持的距离通常可以满足煤粉稳定燃烧的要求。

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4.2.4 比较工况 1 和 2 中 Z 向作用力产生的响应，有减振器时反而比无减振器时要大。这说明减振器没有削弱发动机 Z 向振动，反而加强了其 Z 向振动；而工艺基架的 Z 向振动，有的被削弱，有的被加强。但是，对于 Y 向激励产生的振动，发动机和工艺基架各结构的振动都被减振器减弱了。

4.2.5 比较工况2与3的响应。同样都有减振器，但工况 2 无阻尼，工况 3 有阻尼，各结构的最大响应比无阻尼时要小，但是响应下降幅度不大。从响应的时间历程看，有阻尼时，响应衰减得很快。

4.2.6 对于第 4 工况，即同时作用着水力测功器激励和发动机激励，且又是 Z 向与 Y 向组合，这是一种最不利的振动状态，用来考察工艺基架及发动机的响应是否过大。表 3 数据表明，工艺基架各结构的响应不大，只是发动机响应较大。比如，测功器底架最大速度响应仅为 4.2 mm/s，而发动机最大速度响应为 14.6 mm/s，但此点(208 号节点)位于机组罩壳上，并非位于发动机的机匣，不会影响发动机正常工作。

5 结论

(1) 工艺基架各结构本身的固有频率都在 110 Hz 以上，当承载设备质量后，频率降至 35 Hz 以下，都避开了机组的工作频率。从整个结构系统来看，第一阶频率为 8 Hz，第 20 阶频率为 36 Hz，远低于机组的共振频率。可见，工艺基架结构的设计是合理的。

(2) 从系统的振型上看，低阶频率显示的是减振器和地基支撑弹簧的振型，工艺基架各结构的振型出现在高阶，且减振器、地基弹簧及工艺基架三者之间并无明显的耦合振动。

(3) 减振器减弱了发动机传递给工艺基架的振动能量。或者说，减振器降低了基架振动对发动机正常工作的影响。但是，发动机自身的振动，减振器可能加强其振动(如 Z 向振动)，也可能是减弱其振动(如 Y 向振动)。

(4) 阻尼的存在(小阻尼)，并不能明显降低动态响应的幅值，但从响应时程曲线看，加快了振动衰减的速度。

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换热器网络优化研究进展＝**Recent Developments Concerning the Optimization Study of Heat Exchanger Networks** [刊,汉] / Zhang Junhua, Ying Qijia, Huang Weimin (Power Engineering College under the Shanghai University of Science &Technology, Shanghai, China, Post Code 200093) //Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —201～204

This paper presents the most recent developments both at home and abroad in the study of heat exchanger networks (HEN). Two different methods for the study of heat exchanger networks are compared in detail and a brief description is given of the study of HEN dynamic characteristics. The authors hold that the use of a pinch theory and a mixed integer nonlinear optimization program to other power systems, such as refrigerating and air conditioning systems, can also be conducive to the energy-savings of these systems. In conclusion, the proper orientation of research and development of the HEN has been indicated. **Key words**: heat exchanger networks, pinch theory, mixed integer nonlinear optimization

燃气轮机叶片轮盘振动特性分析＝**An Analysis of the Vibration Characteristics of a Gas Turbine Bladed Disc** [刊,汉] / Zhou Chuanyue. Zou Jingxiang (Department of Aerospatial Engineering and Mechanics, Harbin Institute of Technology, Harbin, China, Post Code 150001), Wen Xueyou, *et al* (Harbin No. 703 Research Institute, Harbin, China, Post Code 150036) //Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —205～209

A brief survey is given of the current status concerning the research at home and abroad of the vibration characteristics of a bladed disc, the key component of a gas turbine. The vibration characteristics studied in this paper pertain to the following elements and components, a single blade, a turbine disc, a blade-disc coupled system and shrouded blades. Also studied are the resonance and flutter occurring in the above-cited elements. In the meantime, a specific example for the calculation and analysis of the relevant vibration characteristics has been presented of the blade and blade-disc coupled system. **Key words**: gas turbine, blade, disc, vibration characteristics, resonance, flutter

垂直浓淡煤粉燃烧方式下炉内拟序结构研究＝**A Study of the In-furnace Coherent Structure under a Vertical Bias Pulverized-coal Combustion Mode** [刊,汉] / Wang Chungang, Zhu Qinyi, Yin Xiangmei, *et al* (College of Energy Science and Engineering under the Harbin Instiute of Technology, Harbin, China, Post Code 150001) //Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —210～215, 225

With the help of a particle dynamic analyzer (PDA) system an experimental and analytical study of the turbulent flow characteristics has been conducted of the in-furnace coherent structure in a tangentially fired furnace under a vertical bias pulverized-coal combustion mode. The in-furnace coherent structure can have an effect on the mixing of the primary air with a main flow field. The results of the above study show that the interaction of the primary air jet flow and the transverse jet flow at the upper stream results in the formation of a wake eddy and a shear eddy respectively at the back-of-flame side and at the flame-facing side. In this regard, there exists in the wake eddy and shear eddy a relatively high turbulent kinetic energy and shear stress, which may play a major role in controlling the diffusion of particles in the furnace. Based on a theoretical analysis the authors conclude that the vertical bias pulverized-coal combustion mode can give rise to certain conditions, unfavorable for the burn-up of pulverized coal particles, thus triggering the formation of slags on boiler water walls. **Key words**: coherent structure, particle dynamic analyzer, vertical bias combustion

增压流化床燃烧煤水混合物管内输送阻力特性研究＝**A Study on the Characteristics of In-tube Transmission Resistance of Coal-water Mixture Burned in a Supercharged Fluidized Bed Furnace** [刊,汉] / Meng Lingjie, Zhang Mingyao (Thermal Energy Engineering Institute under the Southeastern University, Nanjing, Jiangsu, China, Post Code 210096) //Journal of Engineering for Thermal Energy &Power. —2000, 15(3). —213～214, 242

Coal-water mixture can be assumed as pertaining to a generalized non-Newton fluid of two-phase solid-liquid flow and its in-tube flow is characterized by a slip (negative slip) flow phenomenon. On this basis deduced in this paper is a similitude criterion, featuring the flow state of the above-cited coal-water mixture in pipes. Furthermore, a new and simple method has been proposed for determining the in-tube resistance properties of such a coal-water mixture from an engineering perspective. **Key words**: supercharged fluidized bed, coal-water mixture, generalized Reynolds number

GT25000 燃机试验工艺基架动态特性研究＝**A Study of the Dynamic Characteristics of a Technological Base-frame for GT25000 Gas Turbine Test** [刊,汉] / You Guoying (Wuxi Division of Harbin No. 703 Research Institute, Wuxi, Jiangsu, China, Post Code 214151) //Journal of Engineering for Thermal Energy &Power. —2000, 15(3).

—215 ~216, 222

Through the use of a finite element method and a substructure technology a dynamic model of technological base-frame system is set up for a GT25000 gas turbine test. Calculated in detail are the natural characteristics and the dynamic response of the above-cited system. Also discussed is the effect on the system vibrations of a damper and damping action. The results of an analysis show that the technological base-frame possesses relatively good dynamic characteristics and features a rational design. **Key words**: gas turbine test, technological base-frame, substructure, natural frequency, dynamic response

两相流动对流化床燃烧行为的影响=**The Effect of a Two-phase Gas-solid Flow on the Combustion Behavior of a Fluidized Bed** [刊, 汉] / Lu Junfu, Jin Xiaozhong, Zhang Jiansheng, *et al* (Department of Thermal Engineering, Qinghua University, Beijing, China, Post Code 100084) //Journal of Engineering for Thermal Energy & Power. —2000, 15(3). —217 ~219, 238

The measurement along a circulating fluidized-bed boiler height of the gas concentration and the combustion fraction distribution has demonstrated that the major difference between a bubbling fluidized bed and a circulating fluidized one consists in their radically different combustion behavior in a dense-phase zone. Due to a relatively low average particle diameter of the bed material the dense-phase zone flow of the circulating fluidized bed is different from that of the bubbling bed. This will lead to an increase in mass transfer resistance between the gas and solid phase, thus affecting the combustion reaction. The combustion behavior in the dense-phase zone is characterized by a shortage or lack of oxygen. The combustion reaction exists along the height of the circulating fluidized bed boiler and even in a cyclone separator. A combustion model for the fluidized bed dense-phase zone is set up, which takes into account the mass transfer resistance between the gas and solid phase. A comparison with the measured data obtained on an actual circulating fluidized bed boiler indicate that the calculated results are in relatively good agreement with the measured ones. **Key words**: circulating fluidized bed, bubbling bed, dense-phase zone, combustion behavior

非流线型体的滞止浓缩与弥散过程=**Stagnation Concentration Process and Diffusion Process of a Bluff Body** [刊, 汉] / Jin Yan, Wei Yonghua, Xiong Fanfan (Department of Thermal Engineering, Qinghua University, Beijing, China, Post Code 100084) //Journal of Engineering for Thermal Energy & Power. —2000, 15(3). —220 ~222

The authors have come up with a new concept, proposing that both a stagnation concentration process and a diffusion process of particles constitute a basis for the concentrated pulverized-coal combustion technology. An analysis of the mechanism of the above-mentioned two processes is given in the present paper. With the help of a particle dynamic analyzer a study has been conducted of both the concentration process and the diffusion process of a bluff body which assumes the form of a damper, demonstrating for the first time the existence of the stagnant concentration process. The experimental test results show that through the use of the bluff body a concentration or enrichment of the pulverized coal can be readily attained. **Key words**: concentrated pulverized-coal combustion technology, pulverized coal burner, stagnation concentration process, diffusion process, bluff body

采用优化算法分析燃烧火焰辐射光谱求取火焰温度=**Determination of a Flame Temperature from the Analysis of a Combustion Flame Radiation Spectrum through the Use of an Optimized Algorithm** [刊, 汉] / Zhou Jie (Institute of Thermal Power Engineering under the Zhejiang University, Hangzhou, Zhejiang, China, Post Code 310027) //Journal of Engineering for Thermal Energy & Power. —2000, 15(3). —223 ~225

A flame temperature can be determined from an analysis of the radiation spectrum emitted by a gas-burning flame in conjunction with the use of an optimized algorithm. This approach simplifies the calibration of the absolute radiation intensity of a flame as demanded by the conventional two-color method. Meanwhile, it is conducive to a better understanding of the variation relationship of the flame radiation emissivity versus wavelength. The measured temperature values are in good agreement with those obtained by a thermocouple, demonstrating the fairly high precision of the method. Moreover, this also makes it possible to conduct the on-line monitoring of a combustion flame temperature. **Key words**: flame temperature, optimization, radiation intensity

蒸汽动力系统可调节性分析=**An Analysis of the Regulation Possibility of Steam Power Systems** [刊, 汉] / He