第23卷第5期 热 能 动 力 工 程 Vol.23, No.5
2008年9月 JOURNAL OF ENGINEERING FOR THERMAL ENERGY AND POWER Sep., 2008

文章编号: 1001－2060(2008)05－0459－03

某1 000 MW汽轮发电机组轴承载荷灵敏度计算分析

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摘 要: 大型汽轮发电机组是一个多支撑结构, 轴系中任一轴承标高的变化都将影响所有轴承的载荷分配, 因此研究轴承载荷灵敏度对机组稳定运行非常重要。利用传递矩阵法计算了某1 000 MW机组轴系扬度曲线及轴承载荷与灵敏度, 对比分析了计算扬度曲线与实测曲线, 两者在轴系中间吻合较好, 两端差别较大。由计算扬度曲线与实测扬度曲线分别计算了轴系各轴承载荷分布情况, 由计算扬度值得出的同根转子轴承载荷分配较为均匀。结合载荷对标高变化的灵敏度分析了该机组轴承载荷对标高变化规律, 端部轴承对载荷的灵敏度较小, 而中间部位较大。分析结果对该机组运行有指导意义。

关 键 词: 扬度; 转子; 传递矩阵; 汽轮发电机组

中图分类号: TK261 文献标识码: A

引 言

随着机组向大型化方向发展, 机组安全稳定性变得越来越重要。大型发电机组轴系由多根转子组成, 转子在自重作用下会产生挠曲变形。为使机组稳定运行, 各转子必须连接为一条光滑的曲线(扬度曲线), 轴承载荷应该合理分配。

本文利用传递矩阵法计算了某1 000 MW汽轮发电机组轴系扬度曲线及轴承载荷与灵敏度。结合灵敏度曲线分析了该机组轴承标高变化对各轴承载荷的影响关系。分析结果对该机组稳定运行具有一定指导意义。

1 轴承载荷与载荷灵敏度计算方法[1~4]

汽轮发电机组是一个质量连续分布的弹性系统, 轴系可以简化为具有若干个集总质量的多自由度模型。在小变形情况下轴段传递关系为:

$$Z_i = T_{i-1}Z_{i-1} + F_{i-1} \tag{1}$$

式中: $Z_i = [y_i, \varphi_i, M_i, Q_i]^T$,

$$F_i = [0, 0, 0, F_{bi} - m_i g]^T,$$

$$T_i = \begin{bmatrix} 1 & l & \dfrac{l^2}{2EI} & \dfrac{l^3}{6EI} \\ 0 & 1 & \dfrac{l}{EI} & \dfrac{l^2}{2EI} \\ 0 & 0 & 1 & l \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

式中: y_i, φ_i, M_i, Q_i, $m_i g$ 分别代表节点挠度、转角、弯矩、剪力和重力; l, E, I 分别代表轴段长度、惯性模量、截面惯性矩; F_{bi}代表节点反作用力, 轴承节点处F_{bi}为轴承支撑力, 非轴承节点处 $F_{bi}=0$。由传递关系可得:

$$Z_n = T_{1,n-1}Z_1 + T_{2,n-1}F_1 + T_{3,n-1}F_2 + \cdots + T_{n-1,n-1}F_{n-2} + F_{n-1} \tag{2}$$

式中: $T_{k,l} = \prod_{i=k}^{l} T_i$

从上式中取出与轴承相关的 m 个方程, 并考虑两端为自由端边界条件, 即 $M_1 = M_n = 0$, $Q_1 = Q_n = 0$。取位移项展开 m 个方程:

式中: im—第 m 个轴承的节点号, $f_i = F_{bi} - m_i g$。上标 i, j 表示矩阵i 行j 列的元素。由于非轴承节点处f_i 和各轴承标高y_{im}已知, 方程组有唯一解。把所得解带入式(2), 可得轴系各节点处标高、扬度、弯矩和剪力值分布情况:

$$\begin{aligned} & T^{1,1}_{1,i1-1}y_1 + T^{1,2}_{1,i1-1}\varphi_1 + T^{1,4}_{2,i1-1}f_1 + \cdots + T^{1,4}_{i1-1,i1-1}f_{i1-2} = y_{i1} - f_{i1-1} \\ & T^{1,1}_{1,i2-1}y_1 + T^{1,2}_{1,i2-1}\varphi_1 + T^{1,4}_{2,i2-1}f_1 + \cdots + T^{1,4}_{i2-1,i2-1}f_{i2-2} = y_{i2} - f_{i2-1} \\ & T^{1,1}_{1,im-1}y_1 + T^{1,2}_{1,im-1}\varphi_1 + T^{1,4}_{2,im-1}f_1 + \cdots + T^{1,4}_{im-1,im-1}f_{im-2} = y_{im} - f_{im-1} \\ & \cdots \\ & T^{3,1}_{1,n-1}y_1 + T^{3,2}_{1,n-1}\varphi_1 + T^{3,4}_{2,n-1}f_1 + \cdots + \end{aligned} \tag{3}$$

收稿日期: 2007－09－04; 修订日期: 2007－10－23
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$$T^{3,4}_{n-1,\,n-1}f_{n-2} = 0$$
$$T^{4,1}_{1,\,n-1}y_1 + T^{4,2}_{1,\,n-1}\varphi_1 + T^{4,4}_{2,\,n-1}f_1 + \cdots +$$
$$T^{4,4}_{n-1,\,n-1}f_{n-2} = -f_{n-1}$$

假设第 k 个轴承标高变化, 其余轴承标高不变, 将式(3)两边同时对 y_{ik} 求偏导, 易知: $\partial y_{ij}/\partial y_{ik} = 0$, ($j \neq k$), $\partial T/\partial y_{ik} = 0$ 非轴承节点处 $\partial f_i/\partial y_{ik} = 0$, 代入式(3)得:

$$T^{1,2}_{1,\,i1-1}\partial\varphi_1/\partial y_{ik} = -T^{1,4}_{2,\,i1-1}\partial y_1/\partial y_{ik}$$
$$T^{1,2}_{1,\,i2-1}\partial\varphi_1/\partial y_{ik} + T^{1,4}_{i1-1,\,i2-1}\partial f_{i1}/\partial y_{ik}$$
$$= -T^{1,1}_{1,\,i2-1}\partial y_1/\partial y_{ik}$$
$$\cdots \tag{4}$$
$$T^{3,2}_{1,\,n-1}\partial\varphi_1/\partial y_{ik} + T^{3,4}_{i1-1,\,n-1}\partial f_{i1}/\partial y_{ik} + \cdots +$$
$$T^{3,4}_{im-1,\,n-1}\partial f_{im}/\partial y_{ik} = -T^{3,1}_{1,\,n-1}\partial y_1/\partial y_{ik}$$
$$T^{4,2}_{1,\,n-1}\partial\varphi_1/\partial y_{ik} + T^{4,4}_{i1-1,\,n-1}\partial f_{i1}/\partial y_{ik} + \cdots +$$
$$T^{4,4}_{im-1,\,n-1}\partial f_{im}/\partial y_{ik} = -T^{4,1}_{1,\,n-1}\partial y_1/\partial y_{ik}$$

求解上式, 可得各轴承载荷对轴承标高变化的灵敏度。

2　某 1 000 MW 汽轮发电机组轴系轴承载荷与灵敏度计算分析

某 1 000 MW 机组轴系共有高压、低压Ⅰ、低压Ⅱ、低压Ⅲ、低压Ⅳ、发电机和励磁机 7 根转子, 总长约 67 m, 总重约 458 210 kg。轴系共有 13 个轴承, 均为落地轴承。除发电机一励磁机转子为三轴承结构外, 其余均为两轴承结构。该机组轴系被模化为 440 个节点、439 轴段。图 1 为该机组模化简图。

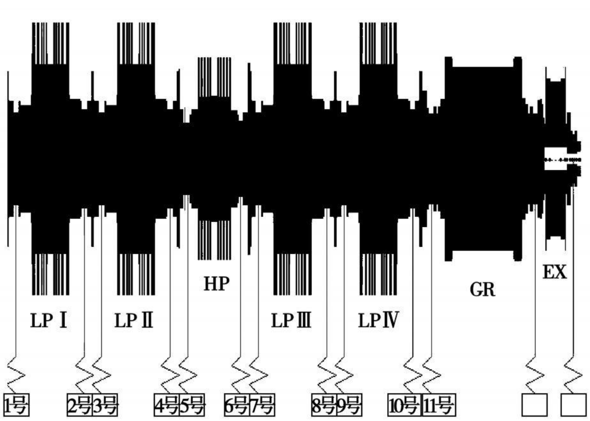

图 1　某 1 000 MW 汽轮发电机组轴系模化图

2.1　扬度曲线计算分析

首先通过传递矩阵法求得各转子两端的扬度, 然后根据各转子两端扬度相等进行逐段连接成整体扬度曲线。实测情况只能测得轴承处的扬度值, 然后根据轴承扬度值求出轴端扬度, 再根据轴端扬度相等逐段连接而成, 其中实测数据中只给出 12 个轴承扬度值, 扬度曲线不包括励磁机段。根据模化数据计算和实测扬度曲线如图 2 所示。

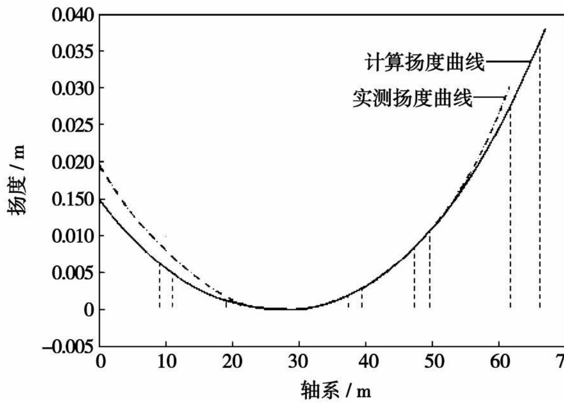

图 2　某 1 000 MW 汽轮发电机组轴系扬度曲线

从图可以看出, 实测与计算扬度曲线在中间部分基本一致, 但两端差别较大, 说明现场安装时两侧轴承扬度较理想情况有偏差。

2.2　轴承载荷计算分析

两种扬度曲线下轴承载荷分配如图 3 所示。

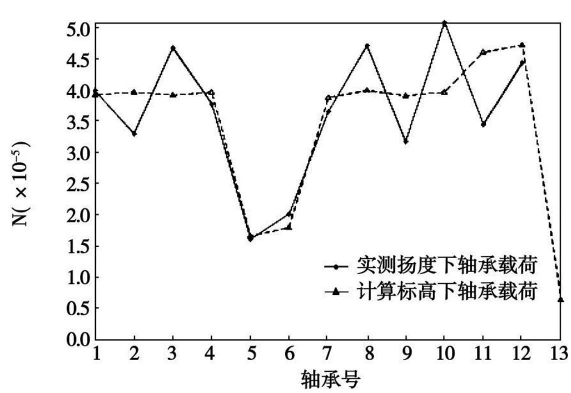

图 3　某 1 000 MW 机组轴承载荷分配图

从图 3 上可以看出, 在两种情况下, 各轴承所支撑的载荷总和值均与转子实际重量相等, 说明轴承扬度变化不改变轴承总的支撑重量。其中 1 号、2 号, 3 号、4 号, 7 号、8 号, 9 号、10 号分别为 4 级低压转子轴承, 模化数据计算情况下这几个轴承支撑重量基本相等。5 号、6 号为高压转子轴承, 高压转子较低压转子轻, 所以 5 号、6 号支撑重量较低压转子轴承小。11 号、12 号、13 号为发电机励磁机三支撑轴承, 励磁机重量较轻, 所以 13 号支撑重量较小。根据测定扬度推算的低压转子重量轴承载荷波动较大, 说明低压轴承扬度较理想情况有偏差, 轴承标高

不合理。

2.3　轴系轴承载荷对标高变化灵敏度计算分析

图4 为灵敏度计算公式，计算该轴系轴承标高变化对轴系各轴承载荷分配影响的灵敏度，各小图中右上角标号表示该轴承标高变化 100 μm，而其它各轴承标高不变情况下对应各轴承载荷的变化。

由图可以看出：

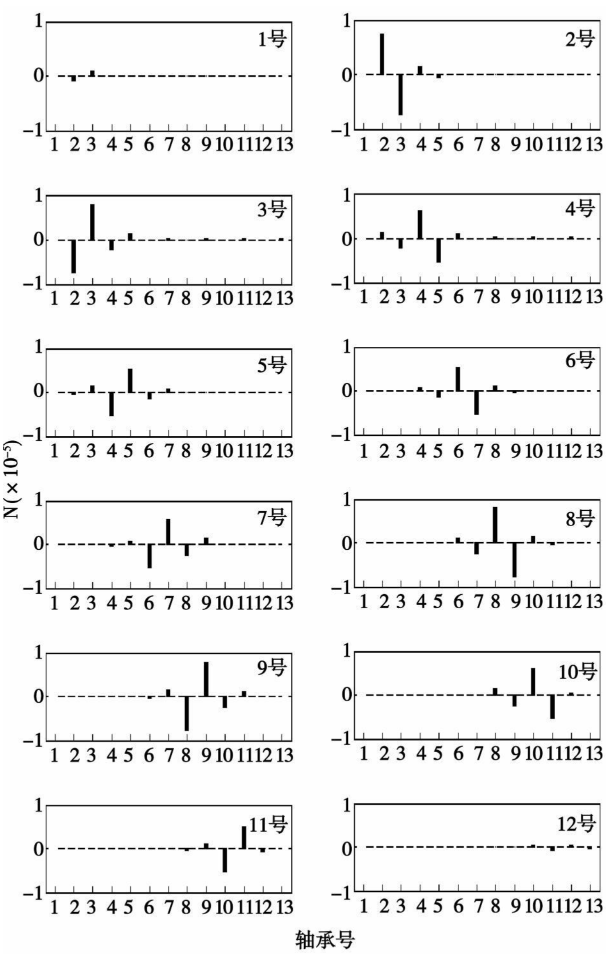

图 4　1 000 MW 机组轴承载荷对标高的灵敏度

（1）1 号，12 号轴承载荷灵敏度很小，即端部轴承标高变化对轴系各轴承载荷分配影响较小。

（2）灵敏度最大的是 2 号、3 号和 8 号、9 号轴承，即这 4 个轴承标高变化对轴系各轴承载荷分配影响较大。

（3）某个轴承标高变化对任意相邻的 2 个轴承载荷的影响相反。

（4）轴承标高变化对本身载荷影响并不一定最大，对相邻轴承的影响可能更大。

（5）轴承标高变化对本身以及联轴器另一侧轴承载荷的影响最大，一般来讲是大小相近，方向相反。

以 3 号轴承为例，说明标高抬高 100 μm 后各轴承载荷变化量如表 1 所示，正值表示轴承载荷增加，负值表示轴承载荷减小。其中 7～13 号轴承载荷基本不变。

表 1　3 号轴承标高改变 100 μm 情况下各轴承载荷改变量

轴承号	载荷变化量/ $N(\times 10^3)$
1	－7.8
2	74
3	－77
4	24
5	－13
6	0.7

3　结　论

本文计算分析了某 1 000 MW 机组轴系扬度曲线与轴承载荷及灵敏度，计算扬度曲线与现场实测扬度曲线中间部分基本一致，两端差别较大，说明实际安装过程两端轴承扬度较理想情况有偏差。通过轴承载荷灵敏度计算，得出轴承标高变化主要影响本身以及联轴器另一端的轴承，两者载荷变化大小相近而方向相反。该机组灵敏度最高的是 2、3 号和 8、9 号轴承，相同的载荷改变量下，这些轴承标高调整量较小。

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（编辑　刘　伟）

燃煤超细颗粒物形成机理及其控制的研究进展＝**Latest Advances in Research on the Formation Mechanism of Superfine Particles During Coal Combustion and Its Control**[刊，汉] / QU Cheng－rui，ZHAO Chang－sui，DUAN Lun－bo，LI Ying－jie（Education Ministry Key Laboratory on Clean Coal Power Generation and Combustion Technology，Thermal Energy Engineering Research Institute，Southeast University，Nanjing，China，Post Code：210096）// Journal of Engineering for Thermal Energy ＆Power．－ 2008，23（5）．－447～452

A survey of the status quo of the study both at home and abroad on superfine particle formation mechanism during coal combustion and its control technology has been given along with a description of the research results achieved worldwide in such aspects as relevant influencing factors，morphological analysis，elementary analysis and emission control etc. relating to the formation of superfine particles．The formation mechanism in question has been expounded as follows：the inorganic matter of coal during combustion will be first evaporated and then homogeneously nucleated or condensed on the existing fine particles．Furthermore，predicted was the development trend of the research on the formation mechanism of superfine particles，their sampling and analytical methods as well as control technologies with the main focus and orientation of superfine particle research to be pursued at the moment being proposed．**Key words**：combustion，superfine particle，formation mechanism，control

基于统计学习理论的叶片动静频率概率设计及敏感性分析＝**Probabilistic Design and Sensitivity Analysis of Blade Dynamic and Static Frequencies Based on a Statistical Learning Theory**[刊，汉] / DUAN Wei，WANG Zhang－qi（Department of Mechanical Enginering，North China Electric Power University，Baoding，China，Post Code：071003）// Journal of Engineering for Thermal Energy ＆Power．－ 2008，23（5）．－453～458

With the chance factors being taken into account，a probabilistic analysis of the inherent vibration frequency of blades has been conducted and a proposition，made that the sensitivity of random parameters constitutes a basis for the dynamic strength reliability design of the blades．With the straight blades of a steam turbine in a test rig serving as an object of study，the randomness of geometrical parameters（including length，width，thickness），material parameters（elastic modulus，density）and rotating speed was taken into consideration．On this basis，a statistical learning theory was applied to obtain the statistical parameters and accumulative distribution function of static（dynamic）frequencies of blades by an integration of the deterministic finite element and radial basis function（RBF）with Monte Carlo simulation method．By adopting a probabilistic sensitivity analytic method，the authors have made a quantitative assessment of the sensitivity of blade static and dynamic frequencies to random input variables．The analytic results can provide positive guidelines for general engineering practice．Furthermore，the authors have compared the calculation results with those obtained by a response surface method，and concluded that the analytic method in question offers a quicker approach than the response surface method．It can serve as an alternative method for the dynamic strength reliability analysis of blades．**Key words**：statistical learning theory，blade，static（dynamic）frequency，probabilistic design，probabilistic sensitivity analysis，radial basis function（RBF）neural network

某 1 000 MW 汽轮发电机组轴承载荷灵敏度计算分析＝**Calculation and Analysis of the Bearing Load Sensitivity of a 1 000 MW Turbo－generator Unit**[刊，汉] / TIAN Yong－wei，YANG Jian－gang（National Engineering Research Center of Thermal Power Plant Vibrations，Southeast University，Nanjing，China，Post Code：210096）//Journal of Engineering for Thermal Energy ＆Power．－ 2008，23（5）．－459～461

A large－sized turbo－generator unit represents a multiple supporting structure，in which any change in the elevation of a bearing in the shafting will affect the load distribution over all the bearings．Therefore，to study the sensitivity of bearing loads is of the utmost importance for the stable operation of the unit．By adopting a transfer matrix method，the authors have calculated the shafting elevation curve，bearing loads and sensitivity of a 1 000 MW turbo－generator unit，comparing and analyzing the calculated elevation curve and the actually measured one．The results show that both curves in the middle of the shafting are in comparatively good agreement with each other．At both ends，however，there is a relatively big difference．The load distribution on various bearings of the shafting was calculated respectively from both the calculated elevation curve and the actually measured one．The bearing load distribution of one and the same rotor obtained from the calculated elevation values was relatively uniform．In the light of the sensitivity of the load to a change in elevation，analyzed was the law governing the change of bearing load with elevation．The sensitivity of the bearings at both ends of the turbo－generator unit to load is relatively small，but that in the middle of the unit，is relatively big．The analytical results can provide some guidance for evaluating the operation of the unit. **Key words**: elevation, rotor, transfer matrix, turbo—generator unit

三维全息谱在诊断负荷诱发的转子热弯曲与标高故障中的运用 = **Application of Three—dimensional Holographic Spectrums in the Diagnosis of a Load—induced Rotor Thermal Bending and Elevation Fault**[刊, 汉] / WANG Xiu—feng, QU Liang—sheng, LIAO Yu—he (Intelligent Instrument and Monitoring/Diagnosis Research Institute, Xi'an Jiaotong University, Xi'an, China, Post Code: 710049)// Journal of Engineering for Thermal Energy & Power. — 2008, 23(5). —462~467

It is extremely common for a large—sized rotary machine to undergo a vibration change of its shafting resulting from a load variation during its operation. An abnormal vibration is often triggered by a change of such operating conditions as the transfer torque and thermal state, etc. of a bearing—rotor system experiencing load variations. The authors have combined the load—induced vibration mechanism with three—dimensional holographic spectrum technology and fully utilized the shafting vibration information indicated by a three—dimensional holographic spectrum to identify the three—dimensional holographic spectrum characteristics of different faults, thus providing a new approach for discriminating load—induced vibration faults. The mechanism and three—dimensional holographic spectrum characteristics of a thermal bending and elevation fault have been analyzed. The verification results obtained from on—site data show that the spectrum characteristics in question resulting from a mechanism analysis enjoy a good ability to identify load—induced vibration faults.
Key words: holographic spectrum, vibration, thermal bending, elevation, load

冲角对高负荷正弯叶栅壁面静压影响的实验研究 = **Experimental Study of the Effect of an Incidence on the Wall—surface Static Pressure of a High—load Positively—bent Cascade**[刊, 汉] / CHEN Shao—wen, LIU Shun—long (College of Power and Energy Source Engineering, Harbin Engineering University, Harbin, China, Post Code: 150001), BIAN Zhao—xi (Harbin Ha—dian Electrical Co. Ltd., Harbin, China, Post Code: 150001)// Journal of Engineering for Thermal Energy & Power. — 2008, 23(5). —468~472

An experimental study has been conducted of the effect of an incidence on the wall surface static pressure of a high—load annular positively—bent diffusion cascade. The results of the study show that when the incidence is positive, the suction surface of a straight—blade cascade exhibits an evident tendency of reverse "C" shaped pressure distribution, which will be intensified with an increase of the bending angle and result in a gradual accumulation of low—energy fluid in the middle of the blade span. Due to a relatively strong reverse pressure gradient streamwise on the suction surface, the air flow in the middle blade span is prone to be separated, thus causing a sharp increase of losses. In a high—load compressor cascade, when the incidence is negative and zero, the adoption of a positively—bent blade design will lead to a better effectiveness in reducing separation and losses than in the case when the incidence is positive. In addition, an excessively large bending angle should be avoided. **Key words**: experimental study, high—load cascade, positive bending, incidence, static pressure

跨音速轴流压气机间隙泄漏流流动特性研究 = **A Study of the Clearance Leakage Flow Characteristics of a Transonic Axial—flow Compressor**[刊, 汉] / ZHANG Yan—feng, CHU Wu—li, WU Yan—hui (College of Power and Energy Source, Northwestern Polytechnical University, Xi'an, China, Post Code: 710072)// Journal of Engineering for Thermal Energy & Power. — 2008, 23(5). —473~477

Clearance leakage flow exercises a major influence on the formation of rotating stall of an axial flow compressor. The authors have conducted a single—passage and multi—passage non—steady numerical simulation by utilizing the transonic axial—flow compressor of NASA rotor 37. The single—passage non—steady calculation results reveal that at an operating condition approximating to compressor stalling speed, there exists a clearance leakage—flow self non—steady behavior at the blade tip. In addition, the non—steady simulation results under two different back—pressure conditions have been compared. When the back pressure at the outlet is comparatively high, the unsteady behavior of the clearance leakage flow is extremely unstable. When the back pressure at the outlet is relatively low, the above—mentioned unsteady behavior is stable. The multi—passage non—steady numerical simulation results indicate that at an operating condition approximating to the stalling speed, when the outlet back pressure is comparatively high, the clearance leakage flow will oscil-