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啮合齿向误差对齿轮承载能力的影响

(哈尔滨·第七　三研究所)　姚绍明　崔震坤*　陈营利　黄清海　高德喜*

摘　要: 提出了一种啮合齿向误差计算方法, 即将齿轮轴线倾角分成两个分量, 分别计算啮合齿向误差, 然后按方向进行叠加; 用这种方法可以分析多种外界因素对齿轮啮合的影响, 如箱体变形、轴端受力、轴线挠曲等; 可以形成适当的空负荷啮合齿向误差, 使工作状态下啮合齿向误差得到补偿; 可以根据齿轮接触情况验算齿轮强度; 在不增加啮合齿向误差的前提下, 合理给定支承平行度要求。

关　键　词: 圆柱齿轮; 啮合齿向误差; 强度

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1　前言

齿轮啮合齿向误差是影响齿轮承载能力的最主要因素之一, 齿轮啮合齿向误差对齿轮承载能力的影响机理见文献[1], 产生齿轮啮合齿向误差的主要因素有齿轮的弹性变形, 包括扭转变形和挠曲变形, 齿轮的螺旋角误差; 齿轮的轴线平行度, 包括箱体轴承孔加工的平行度, 箱体变形产生的轴线偏移及轴的挠曲变形产生的齿轮轴线偏移。本文针对齿轮轴线平行度产生的啮合齿向误差开展分析和研究。

2　齿轮轴线平行度对齿轮啮合的影响

根据 GB3480－83《渐开线圆柱齿轮承载能力计算方法》[1], 在其余条件相同的情况下:

$$S_H \propto 1/\sqrt{K_{H\beta}} \tag{1}$$

S_H: 接触安全系数; $K_{H\beta}$: 齿向载荷分布系数(接触)

$$S_F \propto 1/\sqrt{K_{F\beta}} \tag{2}$$

S_F: 弯曲安全系数; $K_{F\beta}$: 齿向载荷分布系数(弯曲)

$$K_{F\beta} = (K_{H\beta})^N \tag{5}$$

N: 与齿高、齿宽有关的常数[1]

$$F_{\beta y} = F_{\beta x} - y_\beta \tag{6}$$

$F_{\beta x}$: 初始啮合齿向误差; y_β: 齿向跑合量

3　啮合齿向误差的计算及应用

齿轮轴线间倾角是一个空间夹角, 可分为两个分量: 通过主动轮轴线及被动轮轴线上齿宽中点的平面为传动平面, 传动平面内夹角为 θ_p; 通过主动轮轴线与传动平面垂直的平面内夹角为 θ_c。

θ_c 形成的啮合齿向误差为 F_{xc}:

$$F_{xc} = B \cdot \mathrm{tg}\,\theta_c \tag{7}$$

B: 全齿宽;

θ_p 形成的啮合齿向误差为 F_{xp};

$$F_{xp} = B \cdot \sin\theta_p \cdot \mathrm{tg}\,\alpha'_t = \beta \cdot \sin\theta_p \cdot \mathrm{tg}\,\alpha'/\cos\beta \tag{8}$$

α'_t: 端面啮合角; α': 法向啮合角; β: 螺旋角

上式计算将齿面简化成斜面, 由于 θ_p 为微量, 产生的误差小于 0.001 mm, 这个简化是可以成立的, 对于大中型齿轮误差远小于 0.001 mm。

由轴线倾斜产生的啮合齿向误差为 F_x:

$$F_x = |F_{xc} + \lambda_x F_{xp}| \tag{9}$$

λ_x: 补偿系数, 同向时为 1, 反之为－1。

$$F_{\beta y} = |F_x + \lambda_\beta F_{\beta x}| - Y_\beta \tag{10}$$

λ_β: 补偿系数, 同向时为 1, 反之为－1。

对某舰齿轮箱箱体在多种负荷综合作用下进行了有限元计算, 根据计算得出的支撑中心位移情况, 计算出啮合齿向误差及其分布与实舰测试结果趋势上完全吻合。

3.1　啮合齿向误差计算方法的应用

根据啮合齿向误差计算方法可以将多种因素对齿轮啮合的影响进行分析计算, 如轴线平行度误差, 工作状态下箱体的变形, 齿轮轴输入输出端的受力, 轴线的挠曲等等。

3.1.1　箱体变形对齿轮啮合的影响

首先对箱体在多种负荷作用下进行有限元计算, 得出支承中心位移, 再按上述方法计算出对齿轮啮合的影响。

对某舰齿轮箱计算结果见表 1。

表 1

		高压内侧	高压外侧	低压内侧	低压外侧
S_H	增加(%)	－10.985	－7.427	－1.988	－7.895
S_F	增加(%)	－20.545	－14.245	－4.138	－15.094

3.1.2　齿轮箱输入输出端受力对齿轮啮合影响

由于轴承间隙的存在, 齿轮输入输出端在广义力作用下会使轴承支反力产生变化, 使齿轮轴线间产生倾角, 影响齿轮啮合, 只要测出轴承间隙, 就可以计算出外力对齿轮啮合的影响。

3.1.3　轴线挠曲对齿轮啮合的影响

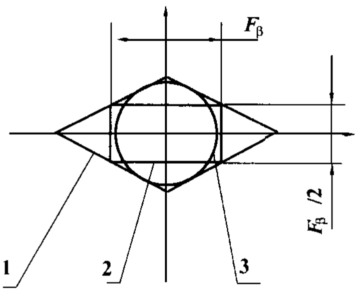
轴线在外力作用下产生挠曲, 首先计算出齿轮两端面中心位移, 再求出齿轮轴线间倾角, 就可以计算出轴线挠曲对齿轮啮合的影响。

3.1.4　啮合齿向误差的补偿

分析计算了齿轮工作状态下啮合齿向误差后,

收稿日期: 1998－12－21; 修订日期: 1999－05－04　*哈尔滨制药总厂

作者简介: 姚绍明(1964－), 男, 哈尔滨·第七　三所三五室工程师, "八五" 预研重点项目《船用齿轮箱支撑与密封技术研究》课题负责人. 通讯处: 150036　哈尔滨 77 信箱 5 分箱



1 啮合齿向误差相等的平行度区域;
2 GB10095 给定的平行度区域;
3 内切圆

图 1　平行度区域比较

即可对之进行补偿，即控制空负荷下齿轮齿向接触长度及方向，形成适当的空负荷啮合齿向误差，使工作状态下产生的啮合齿向误差得到补偿。

当齿轮做接触检查时，着色层厚度基本均匀，可以通过测量接触区长度而间接撑握空负荷啮合齿向误差。

$$F_{\beta x0} = \Delta B / L_j \cos^2\beta \cdot \cos\alpha' \tag{11}$$

$F_{\beta x0}$: 空负荷啮合齿向误差; Δ: 着色层厚度; L_j: 接触区长度

从理论上讲当 $F_{\beta x0}$ 与 $F_{\beta x}$ 绝对值相等时，工作状态下实际啮合齿向误差 $F_{\beta x}$ 应为零。

$$F_{\beta x} = |F_{\beta x} - F_{\beta x0}| \tag{12}$$

$F_{\beta x}$: 实际初始啮合齿向误差

实际生产中由于理论计算本身就存在误差而且制造误差和安装误差都不可避免，因此将啮合齿向误差补偿为零是不可能的。为避免出现过补偿，需取定一个补偿率 λ_o，λ_o 应小于 1，当 $F_{\beta x}$ 计算较准确时 λ_o 可取大些，反之则小些。$F_{\beta x0}$ 计算值为:

$$F_{\beta x0} = \lambda_o |F_{\beta x}| \tag{13}$$

以某船齿轮箱为例进行补偿，使用其箱体变形对齿轮啮合影响的分析结果。在此取 $\lambda_o = 0.8$。着色膜厚度一般为 5 ~ 6 μm[3] 受溶质浓度影响而有所变化，在此取 $\Delta = 5$ μm。由于低压内侧 $F_{\beta x}$ 较小，因此不加补偿。接触安全系数、弯曲安全系数变化如表 2。

表 2

		高压内侧	高压外侧	低压内侧	低压外侧
S_H	增加(%)	14.67	9.20	0	12.14
S_F	增加(%)	30.6	23.93	0	25.04

3.1.5　接触区长度的确定

在工程设计中，齿轮要给出接触区长度，一般是在齿长方向给出一个百分比，在无外界因素干扰的情况下，这是合理的。如果已经分析出工作状态下，外界因素所形成的啮合齿向误差，这样给定是很不合理的，正确的做法是给出接触区的长度百分比，接触区方向及长度允许偏差值，传统的做法只不过是按 100% 接触要求，同时给出一个偏差值。根据前述算例，某船高、低压 Ⅰ 级齿轮接触区给定如表 3。

表 3

齿轮对	高压内侧	高压外侧	低压内侧	低压外侧
齿向接触 %	60	80	100	65
允许偏差 %	20	20	20	20
方　向	后	后	/	前

4　对国标齿轮精度中轴线平行度的探讨

国标 GB10095－88 中平行度的选取为:

$$f_x = F_\beta \tag{14}$$

$$f_y = 0.5F_\beta \tag{15}$$

F_β: 齿向公差; f_x: 传动平面内平行度; F_y 垂直平面内平行度。

其平行度区域为一矩形区域

而根据本文的计算方法，在不增大平行度对齿轮啮合影响的前提下，允许的平行度误差区域为棱形区域。

$$F_x = |f_y \pm f_x \operatorname{tg}\alpha'/\cos\beta| = 0.5F_\beta + F_\beta \operatorname{tg}\alpha'/\cos\beta \tag{16}$$

其内切圆直径 D 为:

$$D = F_\beta(1/2 + \operatorname{tg}\alpha'/\cos\beta)\left(\frac{\cos\beta}{2\operatorname{tg}\alpha'} + 1\right) \Big/ \sqrt{\left(\frac{1}{2} + \operatorname{tg}\alpha'/\cos\beta\right)^2 + \left(\frac{\cos\beta}{2\operatorname{tg}\alpha'} + 1\right)^2} \tag{17}$$

两者平行度允许区域见图 1。

在不增加对齿轮啮合影响的前提下，大大放宽了平行度要求。

5　结论

(1) 计算齿轮轴线间倾角产生的啮合齿向误差时，应将齿轮轴线间倾角分成传动平面内和垂直平面内两个分量，分别计算并按方向进行叠加。

(2) 多数外界因素对齿轮啮合影响都是通过对改变齿轮轴线间倾角来实现的，计算出齿轮轴线间倾角就可以对这一影响进行定量计算。

(3) 通过测量接触区长度，可以计算出空负荷啮合齿向误差。

适当形成空负荷啮合齿向误差，可以使工作状态下啮合齿向误差得到补偿，补偿率 λ。推荐范围 0.5 ~ 0.8; 在设计中对齿轮接触提要求时，不但要给出接触区长度，还应给出方向及偏差值，偏差值可参照 GB10095 给出。

(4) 在设计中给定轴线平行要求时，可以按圆形区域给出，并不增加齿轮的啮合齿向误差。对于标准直齿轮，该圆形区域直径为 0.811 87F_β。

参考文献

〔1〕 马先贵等. GB3480－83 渐开线圆柱齿轮承载能力计算方法. 北京: 中国标准出版社, 1988.
〔2〕 历始忠等. GB10095－88 渐开线圆柱齿轮精度. 北京: 中国标准出版社, 1988
〔3〕 唐定国等. GB3480－199× 渐开线圆柱齿轮承载能力计算方法(送审稿). 北京: 国家技术监督局, 1993.
〔4〕 叶克明等. 齿轮手册. 北京: 机械工业出版社, 1990.
〔5〕 李茹贞泽. 齿轮强度设计资料. 北京: 机械工业出版社, 1984.

(何静芳　编辑)

tion, gas-solid fluidized bed, mixing, non-uniformity, oscillation

径向浓淡旋流燃烧器出口扩锥壁温分布及其对抗磨性能的影响＝**Temperature Distribution at the Expansion Cone Wall of a Radial Dense-dilute Swirl Burner Outlet and Its Effect on Abrasion Resistance**〔刊，中〕/Niu Haifeng, Li Zhengqi, Sun Rui, (Harbin Institute of Technology), et al //Journal of Engineering for Thermal Energy & Power, 2000, 15(1).－15～17

An analysis is performed of the abrasion resistance loss of a central expansion cone at a radial dense-dilute swirl burner outlet. The wall temperature distribution of the central expansion cone under actual operating conditions is studied and determined. The results obtained can serve as a reliable basis for the rational selection of materials for the central expansion cone, contributing to its enhanced high-temperature abrasion resistance. **Key words**: burner, abrasion, wall temperature distribution

层板室壁无相变流动时的冷却性能＝**Cooling Performance of a Laminated Platelet Wall in the Absence of a Phase-change Flow**〔刊，中〕/Wu Huiying, Cheng Huier, Deng Shu (Jiaotong University) //Journal of Engineering for Thermal Energy & Power, 2000, 15(1).－18～19

An analysis is conducted of the liquid coolant heat transfer in a laminated platelet wall. As a result, identified is a performance parameter $m_{1/2}$, which exercises an influence on the platelet wall cooling effectiveness. The above-cited parameter has a bearing on the platelet passage heat exchange area, heat exchange factor and the coolant specific heat. With the platelet thrust chamber serving as an example the authors have determined the effect of the performance parameter $m_{1/2}$ on the platelet inner wall temperature and the temperature difference between the inner and outer wall. **Key words**: laminated platelet wall, cooling performance, thrust chamber, wall temperature

加福煤粉燃烧过程的微观形态观察＝**Microscopic-state Observations of Jiafu Pulverized-Coal Combustion Process**〔刊，中〕/Gu Zhongzhu, Zhang Yonglian, Cai Song (Southeastern China University) //Journal of Engineering for Thermal Energy & Power, 2000, 15(1).－20～22

With the help of an optical microscope and a scanning electronic microscope conducted are the detailed observations of the microscopic-state change relationship of a Jiafu pulverized-coal combustion process. The results of the investigation indicate that there appear in the Jiafu pulverized-coal combustion process five different types of particles, i.e., white, brown and black balls, black lump I and black lump II. The burn-off process is influenced by thermodynamic operating conditions. The key factor in reducing the carbon content of fly ash consists in an attempt to achieve a complete burning of the black lump I and an maximum ignition of the black lump II. **Key words**: pulverized coal, combustion, optical microscope, scanning electronic microscope, fly ash

100MW螺管高压加热器封头应力分析＝**Stress Analysis of the High-pressure Spiral-tube Heater Head of a 100 MW Unit**〔刊，中〕/Lu Yue, Zhang Jianping, Jin Jiadong (Harbin Boiler Co. Ltd.) //Journal of Engineering for Thermal Energy & Power, 2000, 15(1).－23～25

Through the use of a finite element method analyzed and evaluated in this paper is a high-pressure heater head. **Key words**: high-pressure heater, mechanics model, boundary conditions, finite element analysis

啮合齿向误差对齿轮承载能力的影响＝**The Effect of Gear Mesh Error on Gear Loading Capacity**〔刊，中〕/Yao Shaoming, Cheng YinLi, Huang Qinhai (Harbin No. 703 Research Institute), et al //Journal of Engineering for Thermal Energy & Power, 2000, 15(1).－26～27

The authors have come up with a method for calculating gear mesh error. Under this method the gear axial inclination angle is divided into two components with the gear mesh error being calculated separately and then added up as per direction. This makes it possible to analyze the effect on gear mesh of such factors as gear box deformation, axial end loading and axial deflection, etc. A proper no-load gear mesh error may be generated to compensate gear mesh error under operating conditions. It is also feasible to verify gear strength on the basis of gear contact conditions. Under the precondition of an absence of increase in gear mesh error a rational support parallelism can be set. **Key words**: cylindrical gear, gear mesh error, strength

废气复合透平系统的热技术经济学分析和设计优化＝**Thermotechnical Economics Analysis and Design of a Waste Gas Turbo Compound System** 〔刊, 中〕/Tang Lichun (Southern China University of Science &Technology), Pan Jiayan (Guangzhou Municipal Energy Source Planning Design Institute) //Journal of Engineering for Thermal Energy &Power, 2000, 15(1). —28～30

By combining thermotechnical economics theory with BOX nonlinear constraint (compound type) optimization method a thermotechnico-economics analytical study and an optimized design calculation were conducted of a heavy-duty diesel waste gas turbo-compound system (TCS). The method discussed can provide some useful reference data during the scheme design of a power station at the feasibility study stage. **Key words**: waste gas turbo-compound system, thermotechnical economics, optimized design

某舰用冷凝器凝结水含氧量的测试＝**Test of Oxygen Content in the Condensate of a Naval Condenser** 〔刊, 中〕/Xu Yan, Meng Fanzheng, Yin Yuxiang, (Harbin No. 703 Research Institute), et al //Journal of Engineering for Thermal Energy &Power, 2000, 15(1). —31～32, 35

With the help of a novel device for measuring the oxygen content in water a dynamic detection was performed of the oxygen content of condensate at the outlet of a naval condenser working under various operating conditions. The resulting determination of the thermodynamic characteristics of the condenser can provide a requisite basis for its modification design later on. **Key words**: condensate, oxygen content, evaluation test

锅炉有缝电阻焊管制造工艺＝**Manufacturing Technology for Boiler Tube Seamed Resistance Welding** 〔刊, 中〕/Liu Shuzhen, Zhu Hong, Cheng Wanbe (Harbin Boiler Co. Ltd.), et al //Journal of Engineering for Thermal Energy &Power, 2000, 15(1). —33～35

LM5000STIG120 机组余热发电工程电气设计＝**Electrical Design of the Waste Heat Power Generation Project of a LM5000 STIG Unit** 〔刊, 中〕/Sun Shifeng, Hu Guoju, Zhang Qingjiang (Harbin No. 703 Research Institute), et al //Journal of Engineering for Thermal Energy &Power, 2000, 15(1). —36～38

A description is given of the main electrical connection design of a LM5000 STIG 120 unit for Shenzhen Yueliangwan Gas Turbine Power Plant. In addition, the plant auxiliary power supply of the Plant is also briefly discussed. **Key words**: short-circuit current, circuit breaker, reactor, dynamic stabilization, thermal stabilization

燃气脉冲在线吹灰装置及其控制系统的研制与应用＝**Development and Application of a Pulsed Gas-based On-line Soot-blowing Device and Its Control System** 〔刊, 中〕/Li Zhonghua (Shanghai Jiaotong University), Han Tongtai, Liu Jianjun (China National Mine Engineering University) //Journal of Engineering for Thermal Energy &Power, 2000, 15(1). —39～40

The use of rotary air heaters in thermal power plants generally gives rise to soot deposits-related serious corrosion, flue gas high flow-resistance and excessively high exhaust gas temperatures. To cope with the above-cited problems, the authors have developed a pulsed gas-based on-line soot-blower system, using explosive gas to serve as a soot-blowing gas source. In addition, a computer-based monitoring system has also been developed in connection with the soot-blowing unit. Practical use experience shows that the soot blower unit under discussion has the capability to conduct a safe, reliable and