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锥面螺栓联接结构承载能力的实验预测

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【摘要】 本文用模型试验方法研究了以套齿(花键)联接的某发动机高压轴的轴向承载能力,分析了双锥面定位联接结构的载荷—变形规律以及它们与传统的螺栓联接结构载荷—变形规律的区别,讨论了影响双锥面联接结构轴向承载能力的因素,同时对某发动机高压轴的承载能力进行了试验确定,并对其装配工艺提出了改进建议。

一、载荷—变形分析

图 1 示出的双锥面联接结构的联接件(高压涡轮轴)和被联接件(高压压气机轴颈、前锥体、后锥体及调整垫片等)用锁紧螺母锁紧,它与普通螺栓联接结构有两个明显的区别:

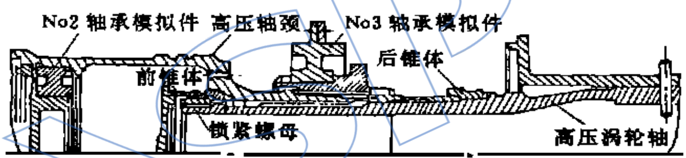

图 1 双锥面联接结构简图

其一是双锥面结构的被联接件中有两处用锥面接触,联接后的总压缩量包括各零件的弹性变形及锥面之间的刚体滑移。此两锥面间的相对滑移的产生见图 2 的分析。当它们受压缩后,要产生弹性变形,零件 2 变形后的位置为虚线所示,Δ_e 为轴向弹性变形,a_c' 为径向弹性变形。因轴颈刚度较大,故可忽略其弹性变形。在结构受压缩载荷前,a 点(零件 2 上)与 b 点(零件 1 上)重合,压缩之后,被联接件产生变形,a 点变形后的位置为 a',b 点变形后的位置为 b',此时 $a'b'$ 反映了两个锥面之间因压缩载荷引起的相对滑移量(刚体滑移),$a'c$ 为滑移的径向分量,ab' 为滑移的轴向分量。

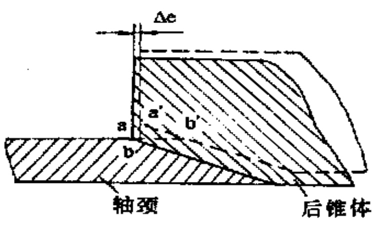

图 2 锥面接触零件的变形与滑移

其二是双锥面联接结构的装配过程不同于一般螺栓联接。由于套齿联接结构的轴向锁紧比较复杂,根据某发动机高压轴装配技术规程要求,需用专用夹具联接高压压气机转子和高压涡轮转子,用液压系统首先对前锥体施加压紧力(88kN),并在卸除夹具所施载荷之前拧紧螺母,拧紧力以反映液压系统压力的压力表指示值下降不超过 0.49MPa 为准。此装配工艺表明,受压件先受装配压力,然后拧紧锁紧螺母,此时受压件继续产生压缩变形,这是加载过程。当锁紧完毕

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后卸去装配压力时，压缩变形有部分恢复，形成卸载过程。

由于双锥面联接结构具有上述两个特点，则锥面之间的滑移在卸载过程中会受到摩擦力的影响，卸载过程的变形关系与加载过程的变形关系不可逆，见图 3。而且卸载变形曲线与锁紧过程的预紧程度密切相关。由于摩擦影响与不同的锁紧状态有关，所以，目前还难以用简单的数学方法表示不同锁紧状态的卸载变形曲线。通过联接结构的原理或模型试验确定与其具体锁紧过程相应的卸载变形曲线，然后依图解法或实验法确定预紧力、松脱载荷等，才是比较可信的和行之有效的办法。

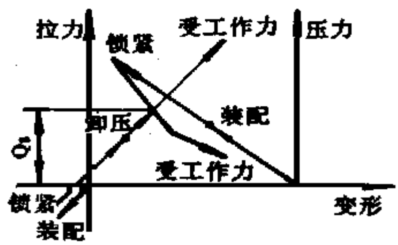

图 3　载荷—变形图

二、模型试验设计

为了分析研究上节提出的关于双锥面联接结构被联接件变形与锁紧力的关系，本试验用环氧树脂塑料模型进行试验。

1. 相似准则　为此首先要保证模型与原型的力学相似，其次要保证结构满足若干相似准则，这样才能实现结构的静力弹性相似，即：(1) 满足几何相似（包括载荷作用位置相似），几何相似常数为 α；(2) 满足载荷相似，载荷相似常数为 β；(3) 模型锥面之间与原型锥面之间的摩擦系数相等；(4) 模型在试验载荷下的应变与原型工作载荷下的应变相等；(5) 模型与原型的泊松比 υ 值相等。

轴颈及涡轮轴联接部分的几何形状与原型完全相同，涡轮轴的整个长度适当缩短，以不影响联接区的变形为准。No2 和 No3 支点用模拟块进行模拟（保证其拉、压刚度相似）。所研究对象除几何尺寸相同外，还应保证配合公差相同。为了确定模型锥面之间的摩擦系数，选择与模型材料及加工粗糙度相同的标准件进行摩擦系数标定，摩擦面涂 201 油膏后，摩擦系数 $f = 0.219$，接近金属原型在同样加工粗糙度时的摩擦系数 ($f = 0.20$)，模型材料在常温下的泊松比 $\upsilon = 0.33$，与金属原型 υ 值接近。模型见图 1。

模型主要承受轴向装配压力、锁紧螺母时的预紧力以及轴向工作载荷，还有套齿传递的扭短。根据量纲分析理论可得如下关系：$P/P_m = \alpha^2 E/E_m$，式中 P、P_m 各为原型、模型的载荷，E、E_m 各为原型、模型的弹性模量。

2. 模型载荷设计　模型载荷大小按上式求得，装配压紧力按装配技术规程施加后，此时后锥体处的 1 号应变片得到相应的应变 ϵ_1 值，当锁紧螺母被锁紧时，ϵ_1 将产生增量 $\Delta\epsilon_1$，它的大小反映了锁紧程度，故选定 $\Delta\epsilon_1$ 作为衡量锁紧程度的控制量。工作载荷将根据原型受力分析结果分别作用到压气机盘及 No2 支点上，其值为 $P = 57.14 P_m$。

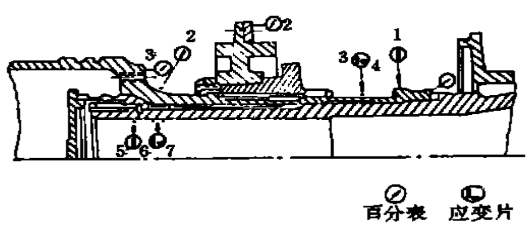

图 4　应变片及百分表安装位置

3. 测量方法　本试验研究中，用电阻应变片测量有关零件在装配锁紧过程及受轴向力时的应变，并用百分表测量有关位置的位移，测量位置见图 4。1 号应变片测得后锥体的周向应

变，它的应变量 ϵ_1 对于联接结构在加载、卸载过程中零件的应变变化比较敏感。当联接结构承受轴向力时，用它的大小来判断联接的紧密性比较合适。可以认为 $\epsilon_1 = 0$ 时结构将松脱（严格地说，因为后锥体与涡轮轴为紧配，ϵ_1 达到小量负值时结构才松脱，因零值容易判别，同时保留一些保险系数）。3 号和 4 号应变片位于轴颈平直段处，该处的应力场比较均匀，可以用 ϵ_3 和 ϵ_4 值计算该处的轴向应力及轴向内力。5 至 7 号应变片测量涡轮轴靠近前锥体部分的应变，利用百分表测量位置 1 至 3 在试验中的位移 Δ_1、Δ_2 和 Δ_3，其差值 $\Delta_{12} = \Delta_1 - \Delta_2$ 和 $\Delta_{13} = \Delta_1 - \Delta_3$ 则反映了被联接件的变形，利用 Δ_1 消除了试验中的刚体位移。

三、装配过程的模拟试验

按规定的原型装配技术规程，模型试验将分两个过程模拟。首先模拟加压力对被联接件的应变、变形进行测定，并研究加、卸载过程的载荷—变形规律；其次，在加装配压力时拧紧螺母进行锁紧，研究这一过程的力学现象。

1. 受装配压力时的力学现象分析　模拟原型装配工艺，在前锥体处加装配压紧力，此时并未进行锁紧，仅为被联接件受压，而联接件尚未受力。其目的是了解被联接件由于存在锥面联接时加载、卸载过程中零件变形、应变的变化特性。测量各测点的应变及位移，数据整理后，可得到零件的载荷—应变（变形）曲线，见图 5。图中反映了被联接件的应变、变形与载荷的关系在加载、卸载过程中是不同的。在加载过程中呈直线变化，在卸载过程中则呈折线变化。此结果充分说明了双锥面联接结构由于存在摩擦力的影响，其载荷—应变（变形）关系在加、卸载过程中不可逆变化。其原因是在加载过程中，被联接件除产生压缩弹性变形外，还在锥面处产生相对滑移，此时由于存在摩擦力，将消耗一部分摩擦功转化为热能放出，所以在卸载时，零件的弹性变形部分恢复，但滑移量因摩擦力的存在需要增加比加载时更多的功才能恢复至原位置。卸载过程并不能增加新的能量，所以锥面不能回到原始位置。如需恢复变形，则需要在卸载后施加与装配压力反方向的拉力（即施加新的功）。此结果说明了双锥面结构将会增加其轴向承载能力。

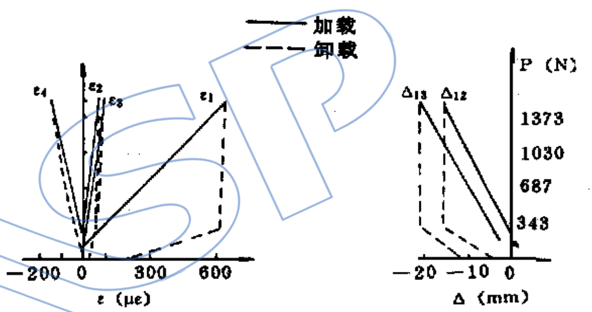

图 5　载荷 — 应变(变形) 曲线

2. 锁紧过程中力学现象的模拟试验　模拟原型在加装配压力后再拧紧锁紧螺母，使被联接件继续受压，联接件同时受拉力。以后锥体应变 ϵ_1 的增量 $\Delta\epsilon_1$ 作为控制锁紧程度的指标。试验中施加装配压紧力后，ϵ_1 值为 $640\mu\epsilon$，拧紧锁紧螺母时分别使 $\Delta\epsilon_1$ 为 $10\%\epsilon_1$，$20\%\epsilon_1$，$30\%\epsilon_1$，$40\%\epsilon_1$，各自在这四种状态下卸除装配压力，此时各零件的应变、变形与装配压力减小量的关系呈线性变化（见图 6），当装配压力完全卸除时，各零件仍然保持相当大的应变及变形。

试验结果反映如下特点：(1) 当拧紧锁紧螺母后，受压零件的压缩变形（应变）达到最大，在卸除装配压力过程中，变形呈线性恢复，但仍保持较大的压缩变形；(2) 结构锁紧以后，被联接件的压缩变形主要决定于拧紧螺母时的锁紧程度（即 $\Delta\epsilon_1$ 的大小）。

本试验结果充分揭示了双锥面联接结构在装配锁紧过程中被联接件和联接件的力学现象。图 7 的曲线表达了后锥体应变 ϵ_1 与压力之间的关系。由于被联接件在装配压紧及卸载过

程中其压缩变形与 ϵ_1 存在着线性关系，所以图中力—应变关系完全可以表征被联接件的压

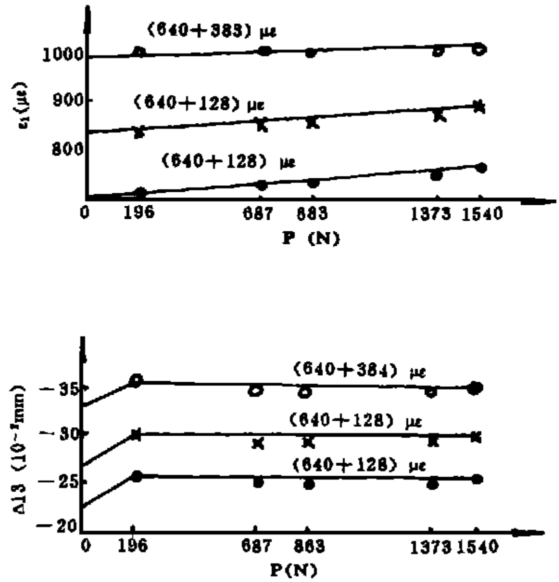

图 6 卸载过程的应变及变形

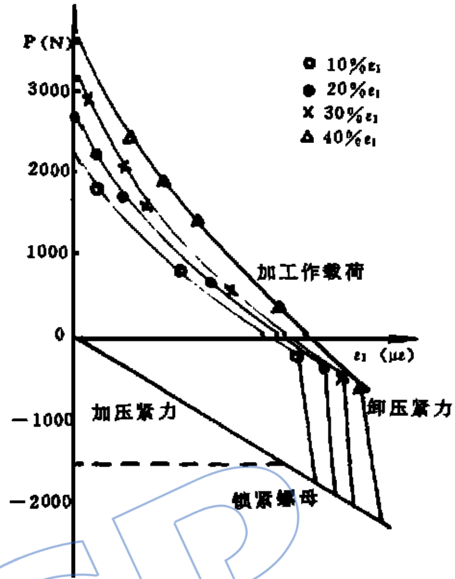

图 7 后锥体应变（ϵ_1）与载荷的关系

缩变形与其载荷的关系，并且与上述双锥面联接结构的力学特性分析结果是一致的。所以本模型试验证实了前述论点的正确。

四、轴向承载能力的确定

根据原型的轴向工作载荷的形式、大小进行模型的模拟。在结构受轴向工作载荷以前，选按前述步骤根据相似要求装配、锁紧 (此时按相应的 $\Delta\epsilon_1=$ 10% ϵ_1，20% ϵ_1，30% ϵ_1，40% ϵ_1 进行锁紧)。加工作载荷时的载荷—应变关系见图 7, 将后锥体应变 $\epsilon_1=$ 0 时的轴向工作载荷定义为松脱载荷 (P_{TL})。图 8 表示了不同锁紧程度下相应的松脱载荷。曲线表明锁紧程度（$\Delta\epsilon_1$） 增加，则松脱载荷呈线性增加。

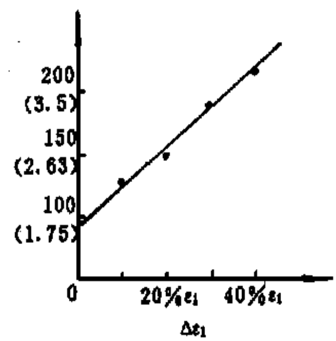

图 8 松脱载荷 P_{TL} 与锁紧程度的关系曲线
(括号内为模型试验值)

COMPREHENSIVE CONDITION MONITORING OF GEAR OPERATION

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ABSTRACT The comprehensive condition monitoring has been proposed by the anthors with six kinds of condition monitoring methods: temperature, vibration, noise, ferrography, infrared spectrum and surface roughness. The research on combined application of these methods has been conducted on a gear test machine (Type CL-100) to develop the technique, method, theory and application of the comprehensive condition monitoring. The comprehensive condition monitoring research is integreted with the pull life experiment. Some of primary experiemental results given in this paper show that the comprehensive condition monitoring with the various methods is much better than that only with one or two methods, especially for monitoring all forms of machine component surface damage such as pitting, wearing and so on.

AN EQUIVALENT WEIBULL DISTRIBUTION METHOD FOR MECHANICAL RELIABILITY ANALYSIS

Wu Liyan, Liu Geng, Wang Buying
(*Northwestern Polytechnical University*)

ABSTRACT A new reliability analysis method is presented which is called quasi-pure-probabilistic method (QPPM). On the basis of the present method, equivalent Weibull distribution method (EWM) is established for the reliability analysis of machine elements. Weibull distribution can express different distribution forms, so it is a more suitable method to describe random parameters with different distribution forms in mechanical reliability analysis. The calculation accuracy of the EWM is higher than that of the equivalent normal distribution mehtod (ENM) in reliability prediction. The present method is intelligible in concept, convenient in use, and has more important significance for reliability prediction of mechanical products with higher reliability requirements.

PREDICATION OF FASTENNING CAPACITY OF SCREWED JOINT STRUCTURE WITH CONE ASSEMBLY

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ABSTRACT Assembly and cone assemble are employed between jointed pants for meeting the requirement of self-centring. The fastenning capacity of rotator screwed joint with cone assembly can not be calculated according to traditional method, because it is not only related to elastical deformation of jointed parts but also to friction condition and slide condition between contact cone surface under simulation conditions of the geometry and assembly technique. A model test has been conducted to research the mechanical behaviour of the jointed parts in assembling and loading process. The load-deformation relation of jointed parts reveals the difference between the plane assembly and the cone assembly. The relation of the former is linear and that of the latter nonlinear. In this research the loose condition of joint structure was defined experimentally as that the strain of cone parts equals to zero and the correlated load is named for loose load (or bearing capacity). Based on the test results the cone assembly jointed structure increases loose load owing to the friction factor. We have

been predicted loose load of real jointed structure in an aeroengine by means of the model test and investigated the factors which have influence on bearing capacity.

NUMERICAL MODELLING FOR GAS DUCT IN TUBOANNULAR COMBUSTOR

Li Changlin, Yao Jixian, Liu Wei
(***Northwestern Polytechnical University***)

ABSTRACT A numerical approach to modelling of hot-gas duct in tuboannular combustor is suggested. The modelling scheme is based on five controlling rules: top and bottom curves on central profile, radii of top and bottom arcs of cross sections, and area of cross sections. A three-dimensional hot-gas duct is regarded as a stacking of finite two-dimensional cross sections constrained by the rules. A brief analysis of computed rules is presented as well. As an example the hot-gas duct of SPEY engine is computed by using this method. Comparison between the computed cross sections and real ones obtained from SPEY technical drawings shows that the method is effective and practicable.

STUDY ON RELIABILITY DESIGN OF TURBINE BLADE

Shi Jinyuan
(***Shanghai Power Equipement Research Institute***)

ABSTRACT A reliability design method is presented for fatigue strength of turbine blades. The method considers static stresses, dynamic stresses and the blade endurance strength as random variables. The scatter effects of the centrifugal tensile stress, the centrifugal bending stress and the gas bending stress are taken into consideration when the distribution parameters of static stresses are determined. The scatter effects of the static natural frequency, the dynamic natural frequency, the stimulus and the amplification factor are considered as the distribution parameters of dynamic stresses are determined. The distribution parameters of the blade endurance strength are determined under the condition that the scatter effects of the corrosion correction factor, the surface quality correction factor, the stress concentration correction factor, the dimension correction factor and the material fatigue limit are taken into account. The distribution parameters of the fatigue stress and the fatigue strength for turbine blades are obtained by the plotting method from the blade endurance strength graphs. The reliability of turbine blades can be estimated in the designing stage by use of interference models for fatigue stress distribution and fatigue strength distribution, which provides a scientific basis for designers to analyze and improve reliability of the turbine blades.

EFFECT OF SOME LOAD FACTORS OF BIRD IMPACT ON BLADE RESPONSE

Yin Jing (***Nanjing Aeronautical Institute***)

ABSTRACT The effect of some load factors of bird impact on blade response is analysed in this paper. These factors include momentum transfer, load-duration, loading location, and spatial distribution of loads. The finite element method is used to compute the nonlinear transient response of the blade by means of simulating a real blade with a rectangular cantilever plate and simulating bird impact loads with shock loads. By computing and comparing the response of the cantilever plate to various load factors, the following