第 5 卷 第 3 期 航空动力学报 Vol. 5 No. 3
1990 年 7 月 Journal of Aerospace Power July. 1990

发动机喘振– 爆燃故障的信号分析

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【摘要】 本文着重介绍某双轴发动机喘振—爆燃故障用 FFT 信号处理机进行诊断和信号分析的方法。文章结合发动机在湍流动态畸变流场下的喘振—爆燃试验研究，介绍了试验设备、测量系统和对发动机 “故障 ” 信号分析的结论。湍流型动态畸变流场下的压气机喘振多为 “漂移型 ” 喘振，表现有随机性。发动机对动态畸变流场的敏感度远高于稳态畸变。利用 FFT 信号分析技术进行故障诊断，有广泛应用价值。它较其它方法精确、迅速、简便。

一、前 言

某双轴发动机在研制中比较顺利的通过了地面台架试车和空中挂飞实验。但在进行高空性能试验时，却连续发生 “放炮 ”。故障发生在发动机低转数过渡状态，折合转数 $\bar{n}_1$= 89% 时，有较大随机性和一定统计几率。

首先作压气机稳态抗畸变网格实验，通过对比实验表明：故障机与原型机稳态抗畸变能力 “无原则差异 ”；其失稳转数和 $\bar{D}$ 较一致；$\bar{n}_1$= 89% 时各种畸变条件下，均未发生异常。

随后进行动态畸变流场条件下的故障再现实验。由于高空台试验耗资昂贵，试验改在地面模拟装置上进行。装置不仅可以再现发动机在高空台的进气流场条件，而且故障再现几率也基本与高空试验时相同。试验首先进行发动机故障再现对比性试验，以后又进行串装试验，最后回高空台进行验证性试验。通过试验找出了故障的主要原因，即特定湍流畸变流场条件造成发动机喘振并导致富油熄火和爆燃。问题得到解决，发动机按时完成首飞任务。

二、实验装置和测试系统

实验装置：以试车台为基础，为模拟高空台发动机进口流场条件，在进口安装了进气流场模拟装置 (图 1)。发动机气流由上方垂直方向进入，先折转 90 并流经扰流板 (其角度可调)。气流折转将形成对涡，并造成发动机进口动态畸变恶劣条件。气流折转点距发动机进口截面仅 2. 1m。发动机出口装有排气模拟装置，模拟高空舱内发动机出口排气条件。

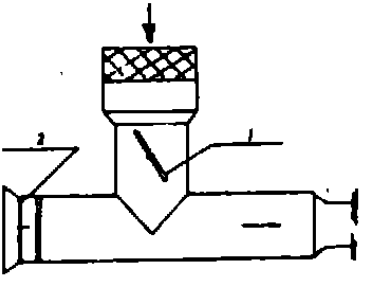

图 1 试验用进口模拟装置
(1. 扰流板；2. 马口铁堵板)

测试系统：

1. 测点及测量管线 稳态测点是根据录取发动机性能要求而确定的。动态测点是为寻找故障时序关系和对压气机进口畸变流场测定而设立。包括：压气机各级动叶顶部测孔，各特征截面的压力及发动机、主副油路压力、转数等共 10～12 处都布置了测点 (如图 2)。

本文于 1989 年 11 月收到。

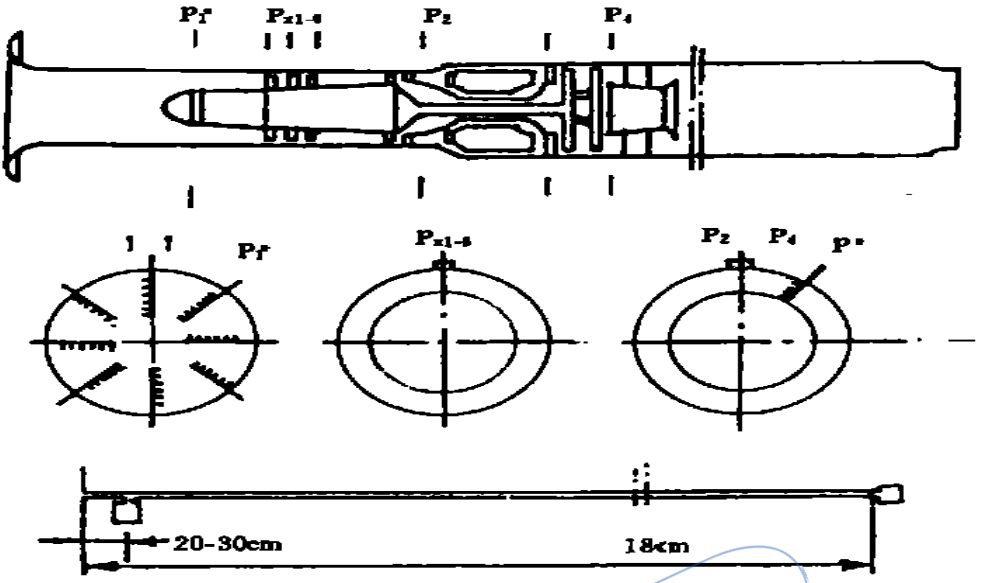

图 2　测点布置图

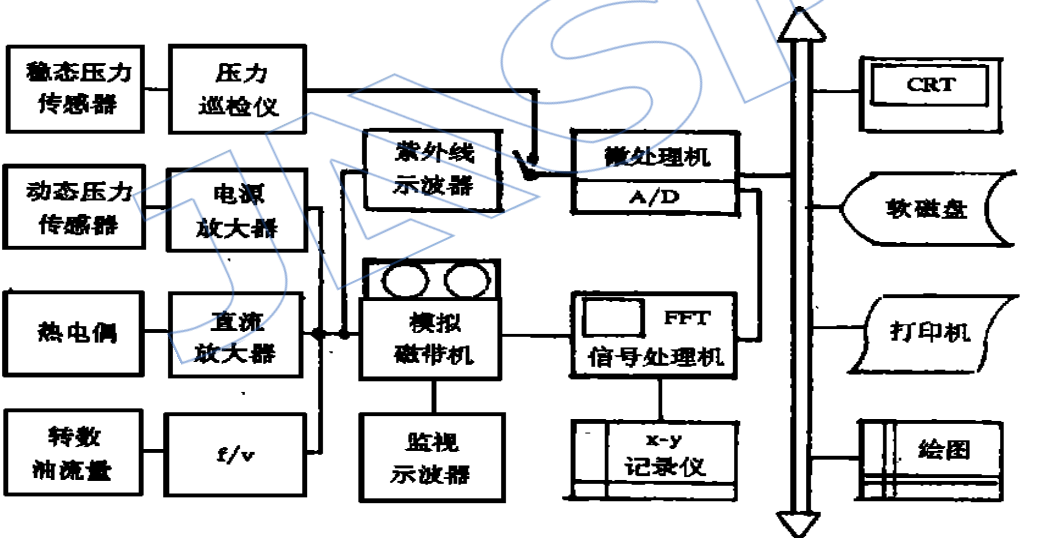

图 3　测量系统框图

2. 仪表和传感器　稳态测量仍用压力巡检仪、推力秤、转数表等台架仪表。动态测量系统（如图 3）：压力传感器用美国 Entran EPV－500 型，精度 0.25% F.S. 信号适调器为提高频率响应特性，选用直流供电直流放大方案，采用美国 vishay2100/2300，频响 DC–15kHz，精度优于 0.1%，增益通常选用 K= 1000 倍，这意味传感器最后输出信号可达 2～8V。大信号传输不仅可以减弱杂波干扰，提高磁带记录精度，同时大信号有足够强的交流分量，便于信号处理机作压力脉动谱分析。磁带机用 TEAC 260/280，频响 DC－20kHz，信号处理机利用 FFT 分析仪可以把信号分解成各种频率成份能量的组合。试验使用 CF–500 双通道 FFT 分析仪，分析范围 DC－20kHz，采样点数 1024 点。主机 Inter 8085。

三、 实 验 过 程

1. 喘振– 爆燃　喘振前操纵员首先发现监控仪表上转数 n_1，n_2 发生脉动摆动约 0.3–0.5%。当油门杆固定在该状态时，T_4^* 向上漂移 10～15℃，同时主、副油路油压、推力发生脉动。与此同时监视示波器也发现压气机各级压力发生严重脉动，其中 P_{x1}（二级顶）最突出，其波形不同于古典失速波，而是杂乱无章的压力脉动波，一串脉动信号后夹杂有更大脉动值（如图 4）。经过多次反复，导致尾部冒火“放炮”，发出低闷的“吐吐”声，同时各截面压力产生锤击波（如图 5，6）。放炮后，进口模拟装置的前方马口铁堵板，被前推成花瓣状。说明发动机气流倒流，压气机已进入全机喘振。

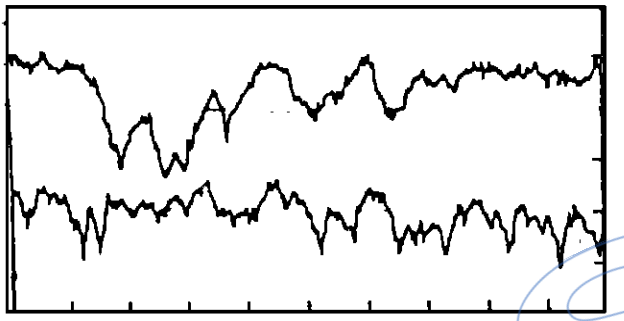

图 4　喘前压力脉动波

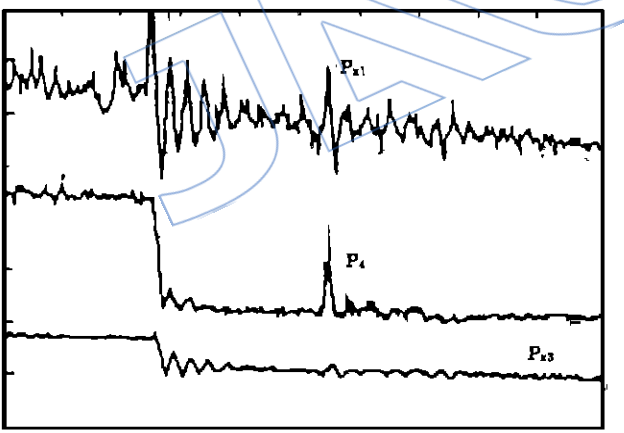

图 5　喘振—爆燃波形

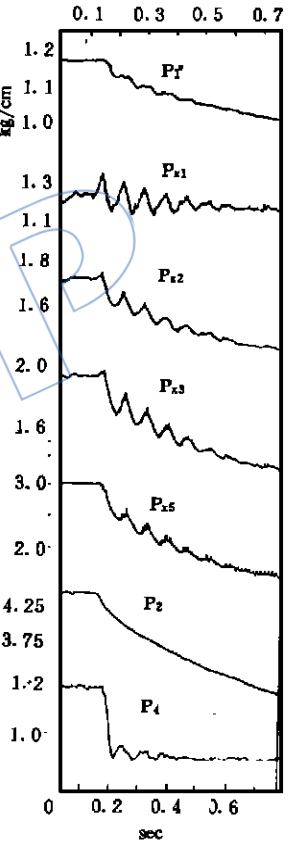

图 6　喘振过程各截面压力脉动波形

2. 进口流场畸变度的测定　为弄清高空台进口流场对发动机的影响，必须测定进口流场畸变指数，通过发动机进口 48 点总压绘制了流谱图（如图 7）。

$$\bar{D} = (P^*_{max} - P^*_{min})/P^*_{cp} = \Delta P^*/P^*_{cp}$$

$\bar{D}$ 畸变指数及动态湍流度 $\Delta P^*_{rpm}/P^*_{cp}$ 和 $\bar{n}_1$ 关系如表 1。

动态湍流度的量级，根据总压管 300ms 多组取样其结果为:

$$\frac{\Delta P^*_{rpm}}{P^*_{cp}} = \overline{\frac{1}{T}\int_T^{\tau}\frac{\Delta P^2 dt}{P^{*2}_{cp}}}$$

表 1　$\bar{D}$ 和 $\bar{n}_1$ 的关系

$\bar{n}_1$	$\bar{D}$	$\Delta P^*_{rpm}/P^*_{cp}$
82.5%	9.05	3.77
85%	9.4	4.38
89%	11.4	5.31
93%	13.15	———
95%	13.88	3.48
97%	14.38	———
100.5% n	14.7n	3.83

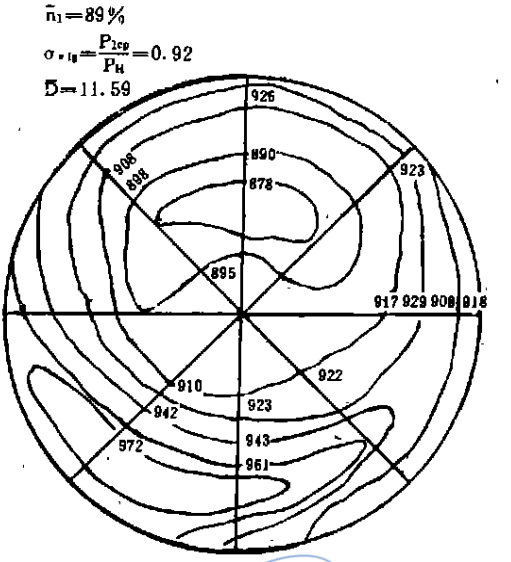

图7　进口流场流谱图

由表可见稳态畸变指数 $\bar{D}$ = 9.05%～14.7%，动态湍流度 $\Delta P^*_{rpm}/P^*_{cp}$ ≈ 3.7%～5.3%，且在 n_1 = 89%时有最大值。这说明发动机是处于严重湍流畸变流场条件下工作，由于稳态和动态畸变及气流对涡影响，自然使压气机工作点向喘振边界方向移动，喘振裕度下降。特别是发动机 $\bar{n}_1 \approx 89\%$ 时这种影响更为突出，因而造成故障。

四、试验信号分析

1. 通过 *FFT* 信号处理机对动态信号进行时域分析表明：在发动机进口流场产生动态畸变时，P^*_1 先产生脉动，压气机即逐步进入喘振。如以压气机二级动叶顶点不稳定突变时间点 P_{x1} = 0 为基准点，则 P_{x3} 产生不稳定点较基准点时间晚 2.3ms，P_2 产生不稳定晚 11.7ms，P_4 产生不稳定点较 P_{x1} 晚 14.1ms。因而可初步判定：喘振是由压气机低压级失稳开始，而后传至高压压气机 P_2 截面。发动机是在压气机进入不稳定工作后，又经 14.1ms 后才导致燃烧室富油熄火。故问题主要矛盾是压气机而不是燃烧室。就压气机喘振强度△P/P 看，也是 P_{x1} 最强，并向后逐步减弱。由此可见低压 2 级是最薄弱环节。

2. 通过信号处理机作频谱分析表明，压气机各次喘振时气流脉动频率均为 13.75Hz，不仅故障机喘振频率为 13.75Hz，改进机喘振频率仍为 13.75Hz（但到高空台则喘振频率全部变成 12.5Hz），这是因为喘振频率主要取决发动机容积大小。不仅 P_{x1} 二级动叶脉动频率为 13.75Hz，其它各截面参数主频也为 13.75Hz，这说明发动机已进入全台压气机喘振。

3. 用信号处理机求二截面信号的相干函数表明：若选 P_{x1} 压力为基准点 A，以其它各级脉动压力分别为 B，求二点相干函数。其主要频率成份相干函数均为 1（COH = 1）这表明后者主要压力脉动源来自 P_{x1}。

$$\gamma_{xy}(f) = |G_{xy}(f)|^2 / G_x(f) \cdot G_y(f) = 1$$

4. 通过信号处理机作功率谱峰值变化表明：压气机在未喘振前，首先有 20Hz 以下低频脉动能量。接近喘振时这种能量逐步集中于 13.75Hz 处（图 8）。13.75Hz 峰值功率谱达到一定量级和持续一定时间后才进入喘振，同时出现周向运动的失速团频率 78Hz，这样对故障机理可作如下理解：由于发动机进口流场的动态畸变和对涡影响，首先造成低压压气机叶背局部分离失速，以后又形成高压压气机堵塞，挡住气流槽道，使气流流动暂时中断，随后，由

于压气机向后抽吸使气流重又恢复，这样使气体微团在压气机内流动—阻塞—再流动。作轴向间歇运动，即“喘振”，此时压气机的气流轴向脉动频率为 13. 75Hz。

5. 根据时域信号分析表明：在压气机喘振后，由于转数下降，燃油调节系统曾造成“误调节”，它根据转数下降增大（或保持）供油，使发动机因进气减少，而产生富油熄火，有时还可能引起燃烧室的积油爆燃，这种脉动压力可以前传并波及各级压气机，但这与压气机喘振完全是两个起因，实验曲线表明（如图 5）：在压气机喘振后 660ms，燃烧室发生爆燃，其涡轮出口温度 T_4 骤增，而其压力 P 脉动频率为 11. 25Hz，此时爆燃压力前传，首先传至高压压气机末级。由此可知：就是这两个完全不同现象喘振和爆燃构成了瞬时的“放炮”。因此，要想解决这一问题，集中要排除主要矛盾进口流场畸变，以控制压气机喘振。

6. 稳态畸变与动态畸变流场的影响：信号分析表明，在稳态畸变试验条件下有时 $\bar{D}\approx 20$，压气机仍保持稳定工作，而在动态畸变和旋涡下，$\bar{D}$ 还不足 14，压气机就进入喘振。可见动态畸变流场对发动机稳定性的影响远大于稳态畸变流场，美国 TF－30 发动机试验也有类似结果。旋涡对压气机叶尖攻角影响很大，特别对无进口导流叶片的超音压气机影响更为明显。

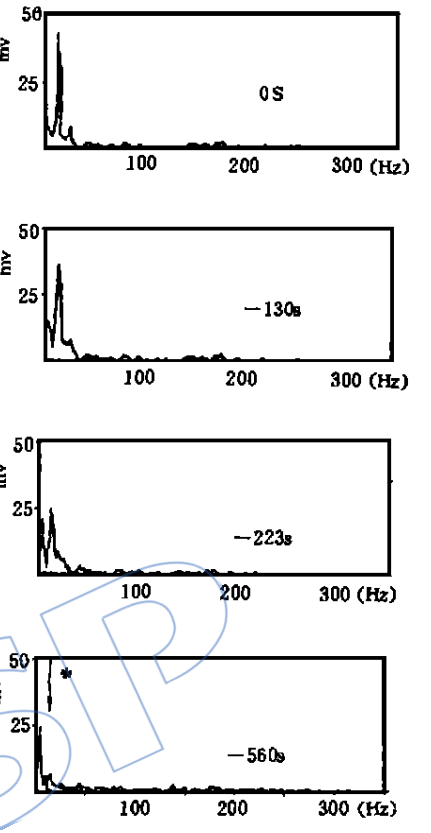

图 8 喘前频谱依时间变化关系

五、结 论

（1）利用 FFT 信号处理机进行发动机动态信号分析与故障诊断方法简便迅速。

（2）发动机在实际飞行中不会遇到实验时所遇的恶劣流场条件。因此发动机可以装机试验飞行，并能确保安全。

（3）湍流型动态畸变流场下的喘振多为“漂移喘振”，它可以在发动机进入稳定工作数十秒或更长时间后再发生喘振，并表现出一定随机性。

（4）随着飞行高度和机动性的不断扩大，发动机对动态畸变的反应要比稳态畸变敏感的多。仅开展稳态畸变试验研究，已不能满足现代发动机发展的要求。

综上所述，本课题根据信号分析，基本弄清了该发动机喘振—爆振的机理及产生“故障”的内因和外因，为发动机按时参加首飞提供了依据。通过两年试飞，飞机已完成飞行包线内各种姿态的最大参数飞行，情况良好。上述成功飞行进一步证实了本实验结论的正确。也证实了信号处理方法的实际应用价值。

第 5 卷 第 3 期 航空动力学报 Vol. 5 No. 3
1990 年 7 月 Journal of Aerospace Power July. 1990

Special Column: EXPERIMENTATION TECHNOLOCY

SIMILARITY RULES FOR TRANSFORMATION BETWEEN HIGH- AND LOW-SPEED MODELS OF HIGH PRESSURE AXIAL COMPRESSOR BLADINGS

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ABSTRACT The similarty rules are based on general aerodynamic similarity theory and drived for the transformation between transonic and subsonic flows, transonic and incompressible flows, and subsonic and incompressible flows respectively, as well as in the cases of full disturbance, according to the linear small perturbation theory, the transonic small perturbation theory and the full potential equation. The validity of the similarity transformations under the inviscid assumption is verified by two-dimensional and quasi-three-dimensional numerical simulations. The reasonableness of the basic concepts and assumptions used in the present work, such as local linearization concept, are testified by the numerical expeiments as well. This work provides an essential basis for the similarity transformation between the high and low-spee models of high pressure axial compressors, and offers an approach to the profile design of a similarity low-speed model and to applieation of experimental data of the similarity low-speed model to the high-speed high-pressure axial compressor bladings.

ADAPTIVE NOISE CANCELLING TECHNIQUE AND BEARING FAULT DIANOSIS

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ABSTRACT In this paper, the adaptive noise cancelling technique is used to improve the signal-to-noise ratio of vibrational data induced from a bearing. Besides the LMS (Widrow) algorithm, the VS(Variable Step) algorithm with more rapid convergent speed and with only a modest increase of computational amount is discussed in comparison with the LMS algorithm. The analysis shows that, when the adaptive noise cancelling technique is adopted to monitor and diagnose a mechanical fault, the VS algorithm is quite feasible. The adaptive noise cancelling techniques at the same state and non-same state are also conducive to identify the bearing fault, but the technique at the non-same state is more applicable than that at the same state.

SIGNAL ANALYSIS TECHNIQUE FOR SURGE-DETONATION OF A TURBOJET ENGINE

Zheng Keyang (*Beijing University of Aeronautics and Astronautics*)
Ge Guohuang (*Le Yang Aeroengine Research Institute*)

ABSTRACT A diagnosis and signal analysis method with FFT signal processer is provided for on surge-detonation of a twin-spoot turbojet engine. The experimental investigation surge-detonation under a turbulent dynamic inlet distortion conditions has been completed by this method and the measuement system and test equipement are described. From the FFT analysis are drawn the conclusions: Most of surges in the turbojet compressor

under turbulent dynamic inlet distortion conditions are "drift-mode" surges and appear randomly; The turbojet is far more sensitive to dynamic inlet distortion than to steady inlet distortion. It is shown that the signal analysis method with the FFT signal processor is of great practical value in the failure diagnosis, and it is a more accurate, reliable and convenient than others.

INVESTIGATION OF INTELLIGENT MEASUREMENT SYSTEM FOR AERO-ENGINE EXPERIMENTS

Wang Weisong (*Gas Turbine Establishment*)

ABSTRACT This paper presents the aero-engine intelligent measurement system which has been developed. The system is original and new in its global design. It integrates the data acquisition, realtime calibration, displacement control, angle tracking, data processing and table printing. The sustem has been used successfully in combustion and turbine testings, its technical and economic effectiveness has been proved remarkable. It is of very great practical value not only in developing aero-engine and its parts, but also in its extension to other military and civil industrial departments.

SUB-MATRICES ANALYSIS APPLIED TO ENGINE FAULTS DIAGNOSIS

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(*Beijing University of Aeronautics and Astronautics*)

ABSTRACT The Gas Path Analysis method for fault diagnosis has be known as an effective method. But the crucial problem is the necessity of measuring a number of aerothermodynamic parameters more than or at least equal to the number of component fault parameters. But the number of measured parameters is always confined by cost and the structure integrity of the engine. The Sub-Matrices Analysis presented in this paper can perform component directed fault diagnosis with less measured parameters. The feature of this method is to combine the fault parameters into groups, in each of which the number of fault parameters equals the number of measured parameters to make the fault parameters solvable with respect to measured parameters. Thus, a set of solutions may be obtained. In order to select the most possible solution (s), the criteria are also given. The numerical investigation shows that this method is very effective to diagnose the malfunction occuring in one or two components which is the usual case at an early stage of engine fault. The problems which are worth careful consideration to avoid false diagnosis are also pointed out. Application of this method to JT9D commercial engine verifies its effectiveness.

HOLOGRAPHIC INTERFEROMETRY MEASUREMENT OF AXISYMMETRIC FLAME TEMPERATURE PROFILES

Xie Mingxing and Wang Zhu
(*Beijing University of Aeronautics and Astronautics*)

ABSTRACT The Double-exposure holographic interferometry is applied to measuring the temperature profiles of axisymmetric spirit-lamp flame and hydrogen flame. A new method is used for searching and thinning interferometric fringes in the computer image processing of holographic interferograms. The temperature profiles of the flames are calculated from measurements of the fringe shift by solving Abel-type integral equation with the Laplace transform. The errors resulted from refraction of the probing rays in holographic interferometry of axisymmetric phase objects are discussed. A simple method is introduced to correct the refractive errors. The effects of the object composition and of small displacement errors of the interferometric fringes on holographic measurements of axisymmetric phase objects are considered too.