第 6 卷　第 4 期　　　　航空动力学报　　　　Vol.6　No.4
1991 年　10 月　　Journal of Aerospace Power　　Oct.　1991

液体火箭发动机混合比故障检测

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本文以某变推力发动机为例，研究当测点有限或故障特征量无法直接测量时，如何有效地检测出发动机的故障。

一、发动机数学模型

1. 正常模型　变推力发动机其系统结构和数学模型的推导详见文献[1]。在这里，我们主要是要研究如何根据系统仅能提供的燃烧室压力测量值检测混合比严重偏高的故障，所以略去其它部件（见图 1），仅考虑燃烧室压力和混合比的动态方程：

$$V_c dp_c/dt = \left[R_cT_c + (1+K)\partial R_cT_c/\partial K\right]\dot{m}_o + \left[R_cT_c - (1+K)K\partial R_cT_c/\partial K\right]\dot{m}_f - R_cT_cp_cA_t/c^*$$

$$dk/dt = R_cT_c(1+K)(\dot{m}_o - K\dot{m}_f)/p_cV_c$$

式中：p_c、K 分别为燃烧室压力和混合比，R_c、T_c 和 c^* 分别为燃烧室气体常数、温度和特征速度，V_c、A_t 分别为燃烧室容积和喉部面积。$\dot{m}_o$、$\dot{m}_f$ 分别为氧化剂和燃料流量，由下式确定：

$$\dot{m}_o = \mu_oA_o\sqrt{2\rho_o(p_o - p_c)},\quad \dot{m}_f = \mu_fA_f\sqrt{2\rho_f(p_f - p_c)}$$

式中：p_o、p_f 为氧化剂和燃料喷前压力，A_o、A_f、μ_o、μ_f 分别为喷注器的流通截面积和流量系数。

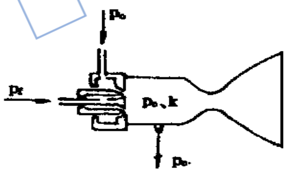

图 1　变推力发动机结构简图

上述方程具有普遍代表性，因此这样的简化使得我们的讨论不只是局限于变推力发动机而具有广泛的适应性。进一步作线性化、无因次处理，引入过程干挠和测量干挠，得到下列以状态空间形式描述的系统模型：$\dot{x} = Ax + Bu + v$，$y = cx + w$。式中：$x = [\delta p_c \ \delta k]^T$，$u = [\delta p_o \ \delta p_f]^T$，“$\delta$”指参数的小偏差量（如：$\delta p_c = (p - p_c^*)/p_c^*$，“*”指额定工况值）；$A$、$B$ 是与发动机工况和结构参数有关的系数矩阵；$c = [1 \ 0]^T$，即输出 y 为 δp_c 的测量值；v 和 w 为零均值的噪声，设：$v \sim N[0, R]$，$w \sim N[0, Q]$，R、Q 分别为过程干挠和测量干挠的协方差。

2. 故障模型　当发动机混合比在某一时刻开始发生变化时，可用下面的故障模型进行描述：

$$\dot{x} = Ax + Bu + v + \delta_tF,\quad \delta_t = \begin{cases}1 & t \geq t_F\\ 0 & t < t_F\end{cases},\quad F = [0,\ f]^T,$$

f 表示故障大小，t_F 为故障发生时间。

二、故障检测算法

1. Kalman 滤波器的设计　针对这样一个多输入并存在随机干挠系统的 Kalman 滤波方程为[2]：$\dot{\hat{x}} = A\hat{x} + Bu + Hr$，式中：$\hat{x}$ 为状态变量 x 的估计值，$r = y - c\hat{x}$ 为滤波器的残差；H 为增益矩阵，它由下面的方程给出：$H = PC^TQ^{-1}$，而 P 是满足如下 Riccati 方程的误差协方差阵

本文于 1990 年 12 月收到。　** 国防科技大学一系　410073

$$AP + PA^T - PC^TQ^{-1}CP + R = 0$$

2. 统计检测方法　在正常情况下, 上面设计的 Kalman 滤波器的残差 r 的采样值 $\{r_i\}$ 应为零均值的白噪声序列。故障发生后, 比如混合比发生跃变, 其均值不再为零[3]。所以, 我们可以用数理统计中的 t 一检验法对残差均值作假设检验来实现对故障的检测并报警[4]:

H_0: r 的均值为零; H_1: 均值不为零。否定域为: $\{|\bar{r}\sqrt{n-1}/s| \geq t_{\alpha/2}(n-1)\}$, 其中 $\bar{r}$、s 分别为采样值的统计均值和均方差, α 为显著性水平, 在这里反映误报警率的大小。一旦 r 采样值落在否定域中, 便认为故障发生并作出报警。

三、仿 真 结 果

我们对发动机的混合比故障发生过程及其故障检测进行了仿真计算。图 2 是一组混合比 δk 和残差 r 在故障前后的变化趋势。从图中可以清楚地看出: 当故障发生后, δk 变为了稳态值, 残差 r 相应发生偏高, 但较 δk 滞后约 8ms 左右。由于检测过程需要 10ms (采样间隙为 1ms, 每次取 10 个点), 所以报警时间大约需要 20ms。

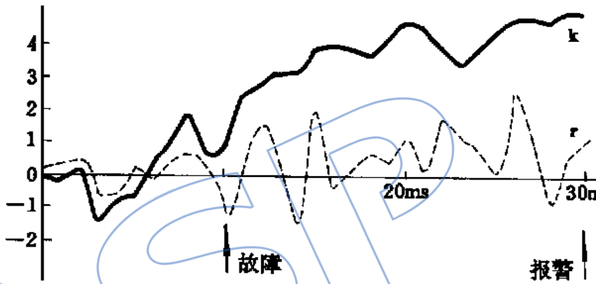

图 2　残差的变化趋势

在仿真时发现, 测量干扰幅度对检测的灵敏性和误报警率的影响很大。这是因为室压与混合比是弱耦合关系, 混合比偏高引起室压的变化很弱, 很容易被室压测量干扰所淹没。表 1 列出了在不同的测量干扰下所能检测出来的混合比偏差, 以及检测不同程度的混合比偏差所需的报警时间和误报警率。从表中可以看出: 当测量干扰较大时, 只有当混合比发生相当大的偏差时才能被检测出来, 报警所需的时间也较长, 相应的误报警率也较高; 在同样的干扰下, 检测较小的混合比偏移需要的时间较长, 误报警的可能性较大。所以在实际应用时应尽量降低测量干扰, 并选择适度的报警限度。

表 1　测量干扰的影响

测量干扰方差	混合比偏差	报警时间	误报警率
0.001	15%	10ms	0.5%
0.001	5%	20ms	2.5%
0.01	26%	70ms	2.5%

以上方法原则上可适应其它液体火箭发动机以及燃气发生器, 因为燃气发生器的混合比偏高会严重影响涡轮工作的可靠性。

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TECHNICAL NOTES

MIXTURE RATIO FAILURE DETECTION FOR LIQUID PROPELLANT ROCKET ENGINE

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ABSTRACT The mixtare ratio failure detection for liquid propellant rocket engine has been studied by means of Kalman filtering and statistical hypotheses testing. A computer simulation of a variable thrust rocket engine demostrates that the algorithm developed by authors can effectively detect mixture ratio deviation. The simulation also gives some significant results useful for the practical application and the further research of the algorithm.

APPLICATION OF COMPOUND LEANED BLADES TO CONTROLLING SECONDARY FLOW

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ABSTRACT Mechanism of controlling secondary flow by using positive leaned blades or compound leaned blades is considered in this paper. The conclusion is that the positive leaned blades produce a converse radial pressure gradient at the hub. Under its action the low-energy fluid in the blade surface boundary layer is migrated from hub to midspan, the blade-to-blade transverse pressure gradient is reduced, passage vortices is weakened and hence the secondary flow losses are decreased. A computation of the compound leaned blades applied to guide vanes in a small engine has been performed as an example. Its results show that by comparison with conventional blades, the degree of reaction and static pressure at the hub of the compound leaned blades are increased, the flow behavior near the hub of working blades is improved; the degree of reaction at the tip is reduced and therefore the leakage losses are cut down too. It is proved that the positive leaned or the compound leaned blades are applicable to controlling the spanwise pressure gradient, the stage reaction and the downstream effect of the secondary flow.

A SMALL FIVE- HOLE SPHERICAL PRESSURE PROBE FOR COMPRESSOR EXPERIMENTS

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ABSTRACT A small five-hole spherical pressure probe instrumentation system is developed and applied to compressor interstage parameter measurement. This instrumentation system has two features: One is smallness of flow disturbance due to small dimensions of the probe head, the other is an advanced data processing method of this system which comprises perfect probe calibration and data processing procedure. The analysis of the test results demonstrates that its performance is stable, its accuracy and data repeatability of its measurements are quite well. This instrumentation system can be applied to verification of the design parameters.