

Fault processing policy based on dual-redundant control law for aero-engine control sensors

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Abstract: A fault processing policy was proposed for the circumstance under which all the dual-redundant closed-loop feedback control sensors went wrong. This policy was based on dual-redundant control law and may maintain the performance of turbofan engines. When pair of controlling sensors went wrong and the primary control law was unable to implement, control system performs the backup control law instead of the primary one so that the fault sensors were isolated from the closed control loop. This fault processing policy may not only avoid increasing engine weight and cost with the additional sensors hardware, but also avoid the error of analytical sensor signal. It can improve the engine mission reliability and control quality.

Key words: aero-engine; control law; fault processing policy; sensors;
health management; digital control

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Nomenclature

H	Flight height, km	p_3	High pressure compressor outlet pressure, MPa
F	Fault signal		
L	Length of fuel valve displacement, μm	T_2	Fan inlet temperature, K
T_a	Inlet air temperature of engine, K	T_5	Low pressure turbine outlet temperature, K
N_h	High pressure spool speed	W_f	Fuel mass flow, kg/s
N_l	Low pressure spool speed		

Suffix

0	Control setting value
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Statistic data indicate that the proportion of on-board sensors faults to all accessories faults of the control system is considerably high. Aero-engine (hereinafter referred to as engine) safety will be seriously menaced with the faults of control sensors, therefore, a mass of scientific researches is made on sensors fault diagnoses and treating method^[1-8]. One means to mitigate the penalties associated with increasing levels of engine safety are the introduction of engine health management capabilities that continuously monitor the condition or health of the engine. Redundancy technology which includes hardware re-

dundancy and analytical redundancy is adopted popularly to upgrade engine dependability^[9]. Hardware redundancy is that there is a couple of same control channels hardware to realize the aim of fault-tolerant control. When one of them faults is isolated from control system and the other one is commissioned. The fault diagnosis based on the hardware redundancy technique has simple structure and accurate detection without the mathematical modeling requirement. However, it will increase the cost and the control system weight^[10]. Analytical redundancy technique of sensors means that using estimated val-

ue according to analytical algorithm instead of redundant member^[11-13].

As a rule, in order to avoid the endangerment resulted by the fault of closed-loop feedback control sensors, all sorts of control sensors are hardware dual-redundant at least. If failure of closed-loop feedback sensor in operation is diagnosed, the fault sensor signal will be isolated from the closed-loop, and closed-loop control system associated with signal from the bake-up sensor. If the bake-up sensor is also in trouble, analytical redundancy estimated value will be adopted which is computed with other faultless sensors signal value.

The control sensors fault processing policy based on dual-redundant control law proposed in this paper is an idea that redundancy technology, which is applied to the control law design. The segmental combined control law designed originally is defined as primary control law. Backup control law may be designed according to the technique and principles. When pair of control sensors go wrong and the primary control law is unable to implement, control system performs the backup control law instead of the primary one so that the fault sensors are isolated from the closed control loop. These will be explored in greater detail in the sequel.

1 Segmental combined control law

Control law of turbofan engine determines its main performance parameters under diversified operation state within the flight envelope. After a thermodynamic cycle of turbofan engine is selected, what the engine performance parameters are depends on what the control law is. The designing objective of control law is obtaining maximal thrust and minimum specific fuel consumption, as well as, preventing component parts of engine from force and heat over loading. Moreover, stability and structural strength of engine is kept in various operation situations within the flight envelope.

1.1 Controlled variable

The choice of controlled variable is the

foundation of control law design. The chosen controlled variable should be tokens of engine operation situation. In addition to thrust and stability, the strength load level of engine components should be signified. If environment condition of engine inlet is invariable consistently, engine thrust and specific fuel consumption is determined on engine pressure ratio and heating ratio of working medium in engine operating theory. In addition, engine strength and heat loading level may be assessed according to engine pressure ratio and heating ratio. However, it is difficult to measure engine pressure ratio and high pressure turbine inlet temperature directly and correctly. The measuring accuracy of engine spool speed are realized easily, so that, low pressure spool speed and high pressure spool speed are important controlled variable customarily, low pressure turbine outlet temperature and high pressure compressor outlet pressure are controlled variable sometimes.

1.2 Segmental combined control law within flight envelope

The control law realized by digital electronic control system for turbofan engines steady operation is a sectional combined one according to inlet air temperature of engine within the flight envelope at present^[14]. The controlled variable is retained of its setting value by adjusting fuel mass flow in order to decrease the influence of flight condition on engine running state, so as to exert engines' powers during each inlet air temperature section. Low pressure spool speed is retained of its setting value when N_1 control law is executed by digital electronic control system, or high pressure spool speed is retained of its setting value when N_h control law is executed. High gas temperature has a harmful effect on turbine durability and gas temperature is an important factor in engine's lifetime, so that, T_5 control law is executed by digital electronic control system if low pressure turbine outlet temperature increase up to setting limit value. For the sake of engine structural member safety mar-

gin is allowable, p_3 control law is realized when high pressure compressor outlet pressure reaches the setting maximum value.

One turbofan engine steady operation mode within the flight envelope is calculated with Gas-Turb under a segmental combined control law. Fig. 1 is sketch map of executing segmental combined control law within flight envelope. N_l control law of the segmental combined control law is realized in the major region of lower Mach number and lower altitude within the flight envelope that digital electronic control system closed-loop control low pressure spool speed. N_h control law is executed in the region of higher Mach number. T_5 control law is function in the upper region of higher altitude within the flight envelope. p_3 control law is function in a little region of low altitude and highest Mach number within the flight envelope. Low pressure turbine outlet temperature sensor is composed of multiple probes connected in parallel, so that, there is little probability of that all probes fault simultaneously. Therefore, N_l and N_h control sensors signal fault processing policy is researched in this paper.

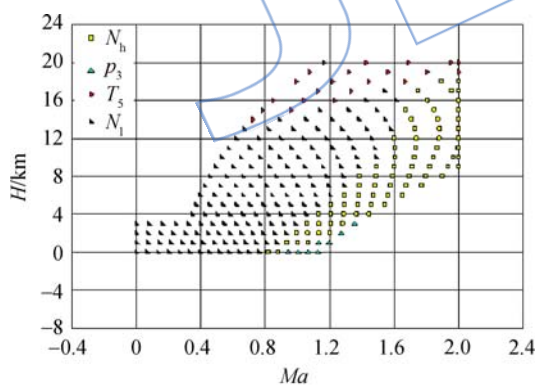


Fig. 1 Sketch map of executing segmental combined control law within flight envelope

2 Dual-redundant control law design

2.1 Primary control law design

The primary one of the dual-redundant control law is the segmental combined control law which aims at achieving optimum thrust and economy as well as stability and structural

strength within the flight envelope of engine. Equated spool speed of compressor increases when inlet temperature reduces according to compressor performance. That means the lower inlet temperature is the higher the equated spool speed of compressor would be. Constant equated speed line becomes a vertical line perpendicular to horizontal abscissa from a curve in the universal performance map of compressor if inlet temperature reduces to a certain extent. That is to say compressor is choked with air flow. In view of fan performance, compressor performance and maximal airflow limit of air inlet duct, equated low pressure spool speed must be limited to its maximum when inlet temperature reduces. Engine inlet temperature increment happens along with flight Mach number increases. When engine inlet temperature is higher than two hundreds eighty eight degree Kelvin, low pressure spool speed increases rapidly if T_a increases continuously on condition that equated low pressure spool speed equal to maximum all the same. Moreover, high pressure spool speed and high pressure turbine inlet temperature goes to the extreme that engine structural strength can endure quickly. Therefore, ascension rate of low pressure spool speed must be decelerated.

Customarily, a turbofan engine adopts N_l control law before either its high pressure spool speed or high pressure turbine inlet temperature reaches the limit which the engine can endure. The setting value of low pressure spool speed which is the aim of closed-loop control is a function of fan inlet temperature. Control setting value of N_l control law is represented by the following calculation equations:

$$N_{l,0} = f(T_2) \quad (1)$$

Where $T_2 < T_a$

When fan inlet temperature becomes T_a , both the high pressure spool speed and combustor outlet temperature reach the limit that the engine can endure. If fan inlet temperature continue increasing, high pressure spool speed and high pressure turbine inlet temperature will increase consequentially. This will result in dam-

age of high pressure spool and high pressure turbine and therefore high pressure spool speed must be controlled when fan inlet temperature increase up to T_a . Control setting value of N_h control law equation is given as follows:

$$N_{h,0} = f(T_2) \quad (2)$$

Where $T_2 \geq T_a$

The overall functional relationship of primary control law is shown in Fig. 2. Low pressure spool speed is closed loop controlled when fan inlet temperature is under T_a , on the other hand, high pressure spool speed is closed loop controlled when fan inlet temperature is above T_a .

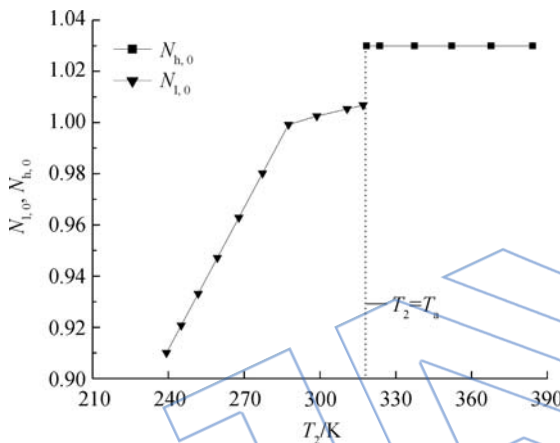


Fig. 2 Sketch map of primary control law

2.2 Backup control law design

Based on the primary control law, backup control law is designed to meet the objective of maintaining the performance of turbofan engines and switching smoothly from primary control law to backup control law^[15]. The principle of the backup control law design is described as follow:

1) The performance of turbofan engine is the same no matter the backup control law or the primary one is executed by DECU (digital engine control unit).

2) Engine operation state is steady and thrust discontinuity is not allowed during switching from primary control law to backup control law.

3) The backup control law should be realized easily by DECU. No new sensor is equipped

so that absolute weight of engine does not increase.

Figure 3 is the backup control law design block flow diagram which shows design technique and steps of designing the backup control law according as the design principle above-mentioned.

One backup control law of the high performance turbofan engine is created according to the principles and technique. First, controlled variable of backup control law was chosen according to the principle 3 of the backup control law design. N_h is the best choice of backup control law controlled variable when fan inlet temperature is under T_a , on the other hand, N_l is preferred controlled variable when fan inlet temperature beyond T_a . So that there is no new sensor and weight of engine does not increase. Second, preliminary backup control law was designed according to principle 1 of the backup control law design aiming at maintaining the engine performance same when the backup control law is executed by DECU. Third, preliminary backup control law was corrected according to principle 2 of the backup control law design. And then, performance parameter such as thrust and specific fuel consumption was calculated adopting primary and backup control law separately with the same program. Contrast the calculation results of adopting backup control law with that of primary one. Estimate whether the difference between them is in accuracy rating. If the answer is "No" correct the backup control law according to principle 1 and principle 2 of the backup control law design until the difference is in the accuracy rating. The closed-loop control setting value of backup control law equations are given as follows:

$$N_{h,0} = \varphi(T_2) \quad (3)$$

Where $T_2 < T_a$

$$N_{l,0} = \varphi(T_2) \quad (4)$$

Where $T_2 \geq T_a$

The functional relationship of the backup control law is shown in Fig. 4.

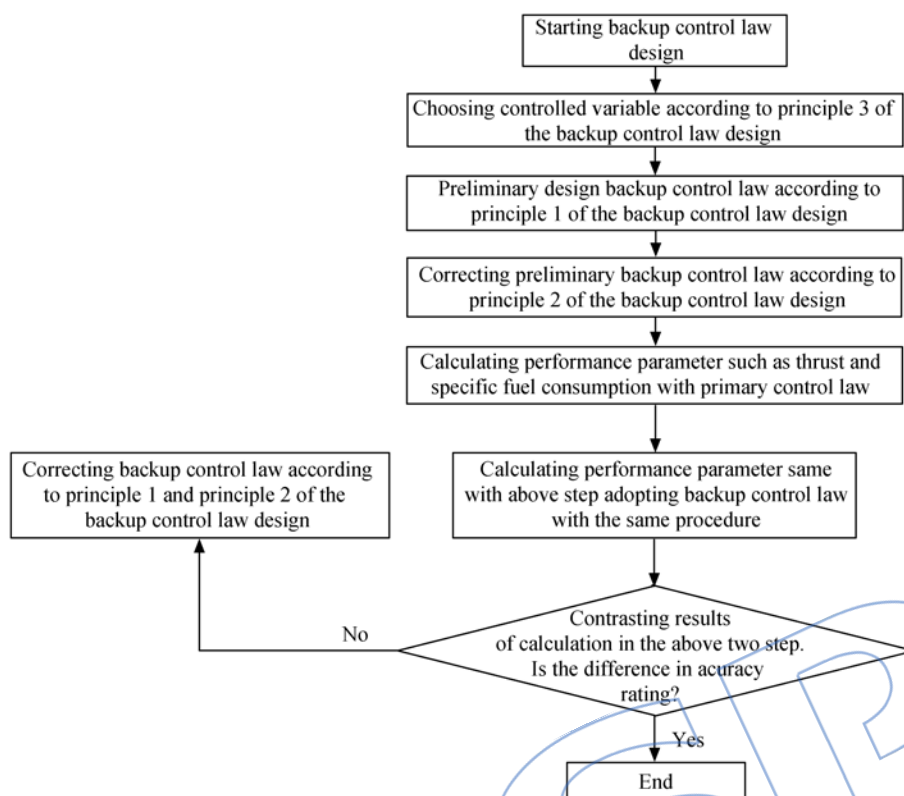


Fig. 3 Block flow diagram of the backup control law design

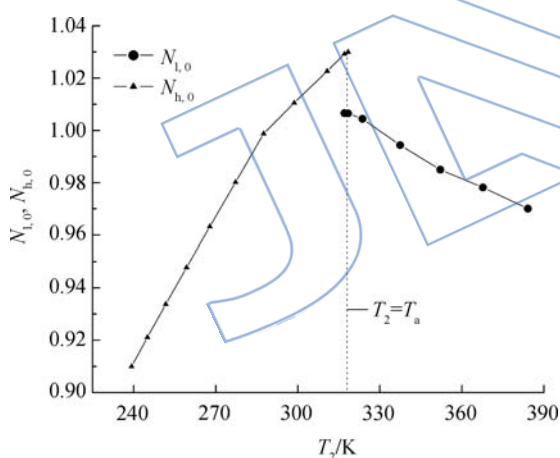


Fig. 4 Sketch map of backup control law

3 Processing method of controlling sensors signal fault

3.1 Implement principium of turbofan spool speed control law

Both the high pressure and low pressure spool speed control sensors which participate in closed-loop control of the turbofan FADEC (full authority digital electronic control) system are hardware dual-redundant. Fig. 5 shows the implementing principium of spool speed segmental

combined control law. DECU confirms the controlled variable which is either N_h or N_l according to the spool speed segmental combined control law under the conditions of T_2 . N_l is the controlled variable in Fig. 5. N_l control law of the segmental combined control law is realized to keep low pressure spool speed equal to its setting value. When measured speed is different from its setting value, the setting value of electrohydraulic fuel valve displacement length, namely, L_0 is calculated on the basis of the speed difference value. Fuel mass flow which is spouted into combustor is quantified by the length of fuel valve displacement. Consequently, the low pressure spool speed of engine operation is adjusted. N_h control law of the segmental combined control law is realized with the same principium.

3.2 Method for utilizing dual-redundant control law to process controlling sensors fault

Figure 6 shows the principium of using dual-redundant control law to process controlling sensors fault without new hardware member (LVDT stands for linear variable differential

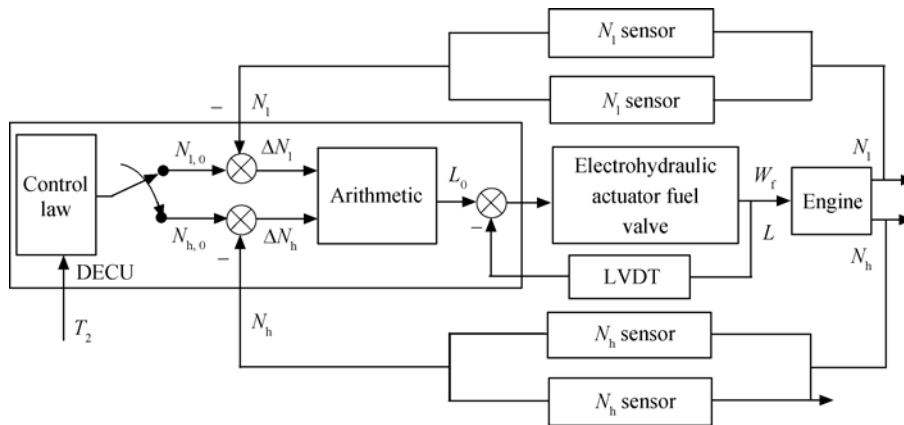


Fig. 5 Implement principle of spool speed segmental combined control law

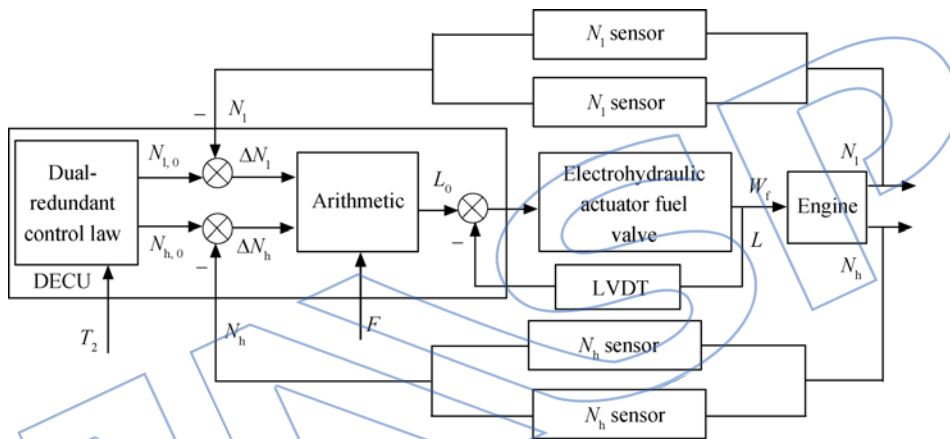


Fig. 6 Principle of using dual-redundant control law to process controlling sensors fault

transducer). DECU calculates the setting values of N_l and N_h , namely, $N_{l,0}$ and $N_{h,0}$ according to the dual-redundant control law. Primary control law is executed on condition that there is no fault signal. When pair of controlling sensors go wrong and the primary control law is unable to implement, control system performs the backup control law instead of the primary one according to the signal F , so that the fault sensors are isolated from the closed control loop.

4 Conclusions

The policy of fault processing for engine control sensors proposed in this paper may have application in all kinds of turbofan engine which is equipped with digital electronic control system. Under the condition that all hardware of closed-loop controlling sensors go wrong, the pre-designed backup control law is executed by

FADEC, so that closed-loop control loop is associated with the back-up controlled variable sensors signal and the fault sensors are isolated from the closed control loop. In this approach, engine holds steady operation station and its mission reliability is enhanced.

Drawbacks of adopting hardware redundancy and analytical redundancy technology to upgrade engine dependability reduce the integrated performance of engine. The method of hardware redundancy result in increasing of accessory number and engine weight, therefore, both the work difficulty and workload are increased in the course of machining, assemblage, production and maintenance. Cost price of engine rises, economic performance of engine falls. There is always a trade in increased weight, cost or reduced performance in order to achieve the extremely high levels of safety. The veracity of an-

alytical redundancy sensor estimated value based on the veracity of onboard real time engine model. Engine is a strong nonlinearity controlled subject which operates in a complicated and changeable environment. Error between the analytical redundancy sensor estimated value and sensor measured signal exists easily. During the period of sensor fault processing, it is unavoidable that engine working state becomes unsteady.

The control sensor fault processing policy based on dual-redundant control law may not only avoid increasing engine weight and cost with the additional sensors hardware, but also avoid the error of analytical sensor signal. It can improve the engine reliability and control quality.

References:

- [1] Jaw L C, Garg S. Propulsion control technology development in the united states; a historical perspective[R]. NASA/TM-2005-213978, 2005.
- [2] Randal R, Daniel E V, Aditya K, et al. Towards in-flight detection and accommodation of faults in aircraft engines[R]. AIAA-2004-6463, 2004.
- [3] LI Yiguang. A GPA diagnostic system for aeroengine applications[J]. Journal of Aerospace Power, 2007, 22(6): 898-908. (in Chinese)
- [4] Kobayashi T, Simon D L. Integration of on-line and off-line diagnostic algorithms for aircraft engine health management[R]. NASA/TM-2007-214980, 2007.
- [5] Volponi A J, Brotherton T, Luppold R. Development of an information fusion system for engine diagnostics and health management[R]. AIAA-2004-6461, 2004.
- [6] HUANG Xianghua, SUN Jianguo. Development of failure diagnosis techniques in engine digital control systems[J]. Journal of Aerospace Power, 1997, 12(4): 416-418. (in Chinese)
- [7] HUANG Kaiming, YIN Zeyong, YANG Zhengshan. Study of rotor speed sensors fault accommodation and test run of turbo-shaft engine[J]. Journal of Aerospace Power, 2007, 22(2): 280-284. (in Chinese)
- [8] LI Benwei, FAN Zhaoyuan, WANG Yonghua, et al. Research on sensor fault diagnosis for a given turbofan engine based on SVR[J]. Journal of Aerospace Power, 2007, 22(10): 1754-1759. (in Chinese)
- [9] Noura H, Theilliol D, Ponsart J C, et al. Fault-tolerant control systems design and practical applications[M]. London: Springer-Verlag London Limited, 2009.
- [10] Jaw L C, Mattingly J D. Aircraft engine controls design, system analysis, and health monitoring[M]. Reston, Virginia: American Institute of Aeronautics and Astronautics Incorporated, 2009.
- [11] SUN Jianguo, HUANG Jinquan, YE Zhifeng, et al. Modern aviation propulsion system control[M]. Beijing: Aviation Industry Press, 2009. (in Chinese)
- [12] Kobayashi T, Simon D L. Evaluation of an enhanced bank of Kalman filters for in-flight aircraft engine sensor fault diagnostics[R]. NASA/TM-2004-213203, 2004.
- [13] Kobayashi T. Aircraft engine sensor/actuator/component fault diagnosis using a bank of Kalman filters[R]. NASA/CR-2003-212298, 2003.
- [14] Нечаяв Ю Н. Control law and characteristic of aviation propulsion equipment[M]. Translated by SHAN Fengtong, CHENG Zhenhai. Beijing: National Defense Industry Press, 1999. (in Chinese)
- [15] JIANG Caihong. Method of dual-redundant control law design for aero-engine[J]. Journal of Aerospace Power, 2011, 26(10): 2364-2370. (in Chinese)