Design and Test Verification of Acceleration Control for the Auxiliary Power Unit Based on N-Dot Acceleration Control Law

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Abstract. The acceleration control law based on the rotor acceleration N-Dot has been widely applied in the design of aero-engine control systems, especially in the design of transient control law. Its advantage lies in the fact that it can guarantee the consistency of the acceleration performance of engine, not affected by engine manufacturing error, component performance degradation, and so on so forth. During the development of full authority electronic control system (FADEC) for an auxiliary power unit (APU), an acceleration control law is designed based on N-Dot and corrected with turbine inlet gas temperature for APU. The modified N-Dot acceleration control law is verified through rig test and the results show that the designed control system by integrating the modified N-Dot acceleration control law with the limit protection control can effectively prevent the engine from surge and over-speed during the acceleration process, and fully take advantage of the acceleration performance of the engine.

1. Introduction
The transient controller design for the aircraft engine takes up a large slice, nearly three-quarters, of the total control law design and development cycle [1]. Transient control must meet stringent acceleration and deceleration design specifications, and ensure that the engine does not exceed its working limits, such as rotor speed limit, maximum operating temperature limit at burner outlet, maximum pressure limit at compressor outlet and surge margin, and other limitations in control system such as gradient of fuel flow.

Advanced engines generally use closed-loop control law based on the rotor acceleration N-Dot, the most prominent advantage of which is that the nonlinear time-varying characteristics of the engine transient state are used to automatically adjust the fuel flow to meet the engine rotor acceleration
demand according to the residual power of turbine and compressor under different environmental conditions, which fully reflects the essential characteristics required by the transient state of the engine [2]. However, the N-Dot control law only focuses on the acceleration performance of the engine, regardless of the operating state of the engine, and thus easily drives the engine into unstable operating limits such as surge, overheating, and flameout.

In view of the problems existing in the N-Dot control law, this paper takes an auxiliary power unit as the controlled object, and proposes a design method to correct the N-Dot acceleration control based on the exhaust temperature T4, according to the dynamic characteristics of the engine rotor. A closed-loop control loop N-Dot control law modified based on T4 is designed, whose effectiveness is verified in the rig test of the engine.

2. Modified N-Dot acceleration control design method based on exhaust temperature T4

The construction of auxiliary power unit is illustrated in Figure 1, consisting of a single-stage centrifugal compressor, a single-stage radial turbine, and an annual circumfluence combustion chamber. The compressed air is extracted through the compressor outlet to output power to the outside devices.

![Figure 1. The structure diagram of an auxiliary power unit](image)

The acceleration of the engine refers to the transient process from the low power level to the high power level of the engine. The main control requirements of acceleration include short acceleration time, no engine surge, no over-speed, no overheating and no flameout.

The acceleration time depends on the amount of surplus torque on the rotor shaft of the engine. According to the engine rotor dynamics [3],

\[ J \cdot \frac{dNG}{dt} = M_T - M_C = \Delta M \]  

(1)

where, \( J \) is the moment of inertia of the engine rotor, \( NG \) is the rotating speed, \( M_T \) and \( M_C \) are the torques of the compressor and the turbine respectively.

The moment balance equation of (1) is equivalent to the power balance equation:

\[ J \cdot \frac{dNG}{dt} \cdot NG = M_T \cdot NG - M_C \cdot NG = P_T - P_C \]  

(2)

where, \( P_T \) and \( P_C \) are the power extracted from turbine and the power consumed by compressor respectively. According to the thermal cycle of the engine,

\[ P_T = (W_a + W_f) \cdot C_{pa} \cdot (T3 - T4) \]

\[ P_C = W_a \cdot C_{pa} \cdot (T2 - T1) \]

where, \( W_a \) and \( W_f \) are the air flow entering the inlet and fuel flow respectively; \( T1, T2, T3 \) and \( T4 \) are the engine inlet temperature, the compressor exit temperature, the turbine inlet gas temperature respectively; \( C_{pa} \) and \( C_{pf} \) are the specific heat of the air and gas at constant pressure respectively. For simplicity, they can be approximated as \( C_{pa} \approx C_{pf} \approx \frac{1}{2} C_p \).

Substituting \( P_T \) and \( P_C \) into the (2),
\[ J \cdot \frac{dNG}{dt} \cdot NG = P_T - P_C = W_f \cdot \eta_b - W_a \cdot C_p \cdot (T4 - T1) \]  

\[ (3) \]

where, \( H_u \) is the fuel lower calorific constant and \( \eta_b \) is the combustion efficiency.

In the process of ground acceleration, the inlet temperature \( T1 \) remains unchanged. The derivative of (3) can be obtained as follows:

\[ J \cdot \frac{d^2 NG}{dt^2} \cdot NG + J \cdot (\frac{dNG}{dt})^2 = \frac{dW_f}{dt} \cdot H_u \cdot \eta_b + W_f \cdot \eta_b \cdot \frac{d\eta_b}{dt} - \frac{dW_a}{dt} \cdot C_p \cdot (T4 - T1) - W_a \cdot \frac{dT4}{dt} \]

\[ (4) \]

when \( dt \to 0 \), the combustion efficiency and compressor performance can be approximately unchanged in a short period during engine acceleration, that is \( \frac{d\eta_b}{dt} \) and \( \frac{dW_a}{dt} \) approximately equal 0, and the acceleration of the engine rotor is also approximately constant, that is \( \frac{d^2 NG}{dt^2} = 0 \) and \( \frac{dNG}{dt} \) = constant. In addition, the same is for \( \frac{dT1}{dt} \). Then (4) can be simplified as

\[ \frac{dW_f}{dt} \cdot H_u \cdot \eta_b = J \cdot (\frac{dNG}{dt})^2 + W_f \cdot C_p \cdot \frac{dT4}{dt} \]

\[ (5) \]

Equation (5) shows that increment of energy from fuel flow \( W_f \) in the acceleration process is used for two parts: one is used in acceleration of engine rotor \( \frac{dNG}{dt} \) and the other is exhausted in the form of heat \( \frac{dT4}{dt} \). When \( \frac{dT4}{dt} \) is too large indicates that the remaining power for rotor acceleration is insufficient, and the engine has a tendency of surge and overheating. Therefore, the fuel flow during acceleration can be appropriately reduced according to the value of \( \frac{dT4}{dt} \).

3. Modified N-Dot acceleration control law design based on exhaust temperature T4

3.1. Integrated Acceleration Control Plan

The full authority digital electronics control (FADEC) with the electric fuel pump as fuel supply device is adopted as APU control system, whose integrated acceleration control logic is shown in Figure 2.
In Figure 2, $PLA$ is the given power lever angle from cockpit; $T4\text{MAX}$ is the known threshold of engine exit temperature; $NGDOT$ is the actual rotor acceleration; $WF$ is the resultant fuel flow demand of the acceleration control plan.

The following focuses on the design of N-Dot acceleration control law modified based on $T4$.

### 3.2. Acceleration Control Law Design based on $T4$ Modification

According to the derivation and analysis in the previous section, modified N-Dot acceleration control based on $T4$, uses the PID controller in the N-Dot closed-loop control and $T4$-Dot to modify the expected engine rotor acceleration $NGDOTr$ during the acceleration process. The control loop schematic diagram is shown in Figure 3.

![Figure 3. N-Dot control loop](image)

where, $s$ is the Laplace operator; $P$ is the proportional gain; $K$ and $C$ are constants.

The control algorithms are as follows.

$$WFAC = P \cdot (NG_r - NG)$$ (6)

where,

$$NGDOT_r = \begin{cases} 
K \cdot NGDOT & T4Dot > C \\
NGDOT & T4Dot \leq C 
\end{cases}$$

$$NG_r = \int NGDOT \cdot dt$$

Make appropriate transformation to (6),

$$WFAC = P \cdot (\int NGDOT \cdot dt - \int NGDot \cdot dt) = P \cdot (NGDOT_r - NG)$$ (7)

Equation (7) indicates that the N-Dot proportional control is equivalent to pure integral closed-loop control. The actual rotor acceleration $NGDot$ are contained in the control law, which avoids the influence on numerical stability and engineering compromise disposal resulting from tracking sensitivity in the direct measurement of $NGDot$ [4].

The change rate of turbine exit temperature $T4Dot$ only works as the adjusting parameter but not acts on the loop directly. When $T4Dot$ rises to the specified threshold, it indicates the energy ratio for rotor acceleration reduces despite the increasing fuel supply. At the same time, exorbitant $T4Dot$ is also a precursor of the engine acceleration approaching stall/surge. The control plan reduces the expected rotor acceleration $NGDOTr$ and then reduces the fuel flow demand $WF$ during acceleration, which prevents the engine accelerating from surge.

### 4. Rig test verification

After completing the design of control law and control system, a series of verifications in test rig [5, 6] were carried out, including electric fuel pump-fuel pressure-motor speed characteristic test, APU power-engine speed characteristic test, engine ignition test and engine steady-state power output test. More than 20 full-state rig tests have been carried out. In the process of engine start-up, operation and power output is stable and reliable. The test results with N-Dot acceleration control law are shown in Figure 4 and Figure 5, where the horizontal axis is time in seconds, the left longitudinal axis is percentile speed NG and the right longitudinal axes are dimensionless parameters of rotor acceleration N-Dot, T4 change rate T4Dot, fuel supply WF and exit temperature T4.
Figure 4 shows the normal test data with modified N-Dot acceleration control law based on T4, whose acceleration time from 65% to 80% is about 3.5s. To verify the corrective limit effect of T4 in the control law, the threshold of T4Dot is reduced and the fuel supply decreases accordingly as shown in Figure 5. Under this circumstance, the acceleration time from 64% to 78% is about 4.3s, which is less than 3.5s and implies that the modified N-Dot acceleration control law based on T4 is effective.

5. Conclusion
For an APU, the relationship of basic thermodynamic parameters in the process of engine acceleration is analyzed based on the equations of engine rotor dynamics and thermodynamic cycle. A novel exploration on overcoming the inherent defects of N-Dot control method is made and implies that pure N-Dot control easily causes engine to surge or overheat, so the N-Dot acceleration control law is modified based on T4. Through the equivalent transformation, the direct measurement of the acceleration of the engine rotor is avoided. The rig test results show that the control plan is effective and feasible.

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