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ANALYSIS OF THE AERODYNAMIC CHARACTERISTICS AND ITS INFLUENCE OF TURBOMACHINERY IN TRANSITION STATE

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Abstract

This paper discusses and classifies the transition states in real operation of aero engines .The common characteristics of aerodynamics and thermodynamics during the transition of an aero-engine are summarized.The variation characteristics of typical parameters are presented for the process of aerodynamic and thermal changes in the transition operating state of an aero-engine.A typical turbofan engine model was selected and the typical transition state characteristic change process analysis was carried out. The change characteristics of aerothermal force during turbine transition are summarized, and a transition characteristic description method that can be applied to engineering is presented.

Keywords: aero-engine,turbine,transition,simulation

1. Introduction

An aero-engine is a complex mechanical product with multiple components working together, and it has to go through various working states throughout its working envelope, including stable working state and unstable working state. Usually, the unstable operating state is also called transition state, and the typical transition states are starting, acceleration, deceleration and other processes. Usually, the performance and parameter matching of the main components of an aero engine/gas turbine are based on the steady state of each component, while in its transition state, the actual performance of each component deviates from the steady state due to the rapid change of engine operating parameters over time, and the difference between the changes of several components may exceed their design expectations. The ITAT safety report also shows that most of the accidents of aircraft and engines occur in the transition state. In the transition state of an aircraft engine, the power of the turbine and the compressor are not balanced, and the acceleration and deceleration characteristics of the engine depend on the residual power of the turbine and the rotor inertia characteristics. Because the rotating parts have relatively larger inertia, the non-stationary characteristics have more obvious hysteresis effects.

Transition states in aero engines are discussed and classified, their common characteristics are summarized, hysteresis effects are discussed and analyzed in this paper.

2. Transition state classification

When some or all of the engine performance-related variables change over time, it enters transition state operation. Generally speaking, the transition state will respond to larger and obvious performance changes in a shorter time period relative to the stable cruise state.

Figure 1 shows the variation of its compression system performance in a typical transition state of an aero-engine.For example, when the aircraft needs to take off in short distance, the engine needs to increase quickly from the idle state to the maximum speed to ensure the takeoff thrust, and when the aircraft needs to quickly reduce the speed from the cruise state to the idle state during the landing process. Generally speaking, the transition state mainly contains ground start, windmill start,

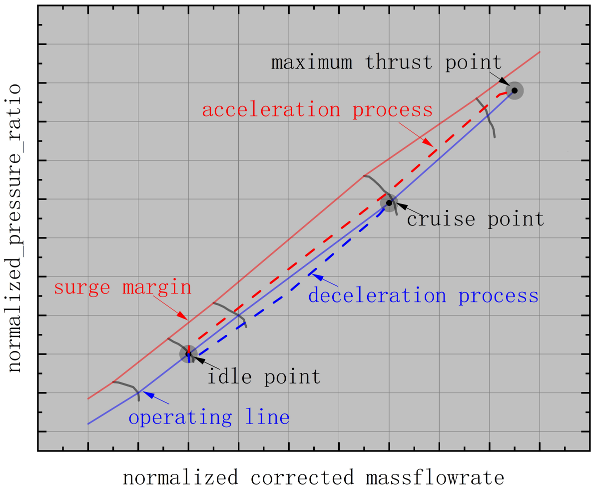

Figure 1 – Aero-engine transition state diagram

cold start acceleration, rapid acceleration, rapid deceleration, slow acceleration, slow deceleration, encounter acceleration and other processes. Because the starting process is generally studied and discussed by special, this paper will not discuss the processes of ground start, windmill start, cold start acceleration, etc.

This paper will focus on the aerodynamic and thermal phenomena during rapid acceleration, rapid deceleration, and hot reslam process.

2.1 Rapid acceleration

Rapid acceleration is a very common phenomenon in the operation of aircraft engines. Especially jet fighters are often required to perform complex combat maneuvers when performing combat missions. As shown in the figure 2,during rapid acceleration of an aircraft engine, the operator performs a step-abrupt operation through the Power lever angle (PLA). Each PLA position corresponds to a given speed expectation value. Due to the step increase of PLA, the expected value of the given PLA corresponding to the speed is higher than the actual engine speed. In response to this action, the control system increases the fuel flow at a predetermined limiting rate until the desired speed is reached. Due to the additional fuel, the power produced by the turbine will be more than the power required by the compressor. The speed of an aircraft engine's high-pressure or low-pressure shaft will then increase rapidly. Until the rotational speed reaches the corresponding position of PLA, the rapid acceleration operation finished. During the rapid acceleration, the physical speed of the aero-engine increases sharply, the matching of aerodynamic and thermal parameters faces serious imbalance, and the distance between rotating and stationary components also has complex changes, which may induce serious aerodynamic problems such as surge.

2.2 Rapid Deceleration

Corresponding to the rapid acceleration, the rapid deceleration process is also often seen in the daily operation of the aircraft. As shown in the figure 3,when there is an abrupt step-down in power lever angle (PLA), resulting in a given PLA corresponding to a lower speed expectation than the actual engine speed, deceleration begins as the PLA decreases. In response to this action, the control system reduces the fuel at a predetermined limiting rate until the desired speed is reached. Due to the additional fuel flow reduction, the power produced by the turbine will be less than the power required by the compressor. The speed of the aero-engine high or low pressure shaft system is then rapidly reduced. Until the speed reaches the PLA position, the rapid deceleration operation finished.

2.3 The hot reslam or Bodie

The hot reslam is a kind of rapid power lever operation of an aircraft operation process.It is also referred to as a Bodie, being named after a US air force pilot who first used the manoeuvre during

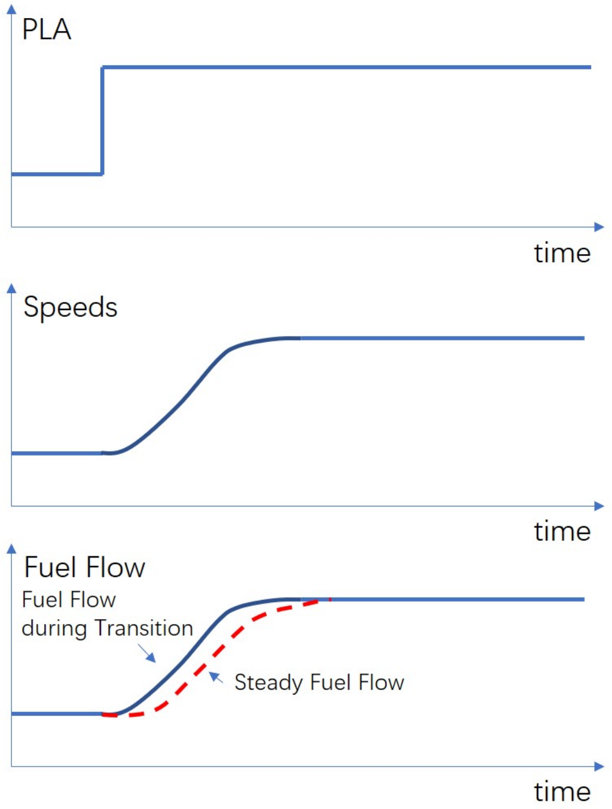

Figure 2 – Engine performance parameters versus time during rapid acceleration

engine flight trials. As shown in the figure 4,The engine is first operated at high power for at least 5 minutes and the engine is fully warmed up. Then deceleration is performed (power lever is pulled down with no more than 1s time) to near idle, followed by rapid acceleration to high power state.
During the hot reslam, the engine decelerates first, the engine speed decreases, the air or gas temperature in each cross section drops, the air/gas temperature will be lower than the temperature of the engine components, and the components will heat the air/gas. When the engine accelerates instantaneously, the heating of air/gas by the components is equivalent to increasing the additional fuel , resulting in an upward shift of the engine operating line compared to the conventional acceleration process; at the same time, this heating process (so called heat soak) affects the flow capacity between the multi-stage components of the high-pressure compressor, resulting in a change of component characteristics and a reduction of the surge boundary.
From the above three typical transition states, it can be seen that acceleration and deceleration are the two most important processes of an aero-engine. The transition state will mainly cause the following problems.
(1) The shaft system composed of turbine-compressor presents structural and aerodynamic strong coupling, and the power mismatch caused by the performance of the transition state causes a series of aerodynamic, structural and control problems.
(2) In the transition state, the aero-engine's own capacitive cavity characteristics will cause its transition process to show hysteresis effects .
(3) The rotating shaft has a large energy storage capacity, and the blade and magazine metal heating effect in the gas turbine has a slow and large change process, further increasing the multivariable characteristics of the transition state characteristics.
4) In the transition state, the main flow paths and air systems show aerodynamic imbalance, further inducing a series of problems such as axial force reversal, gas backflow and gas intrusion.

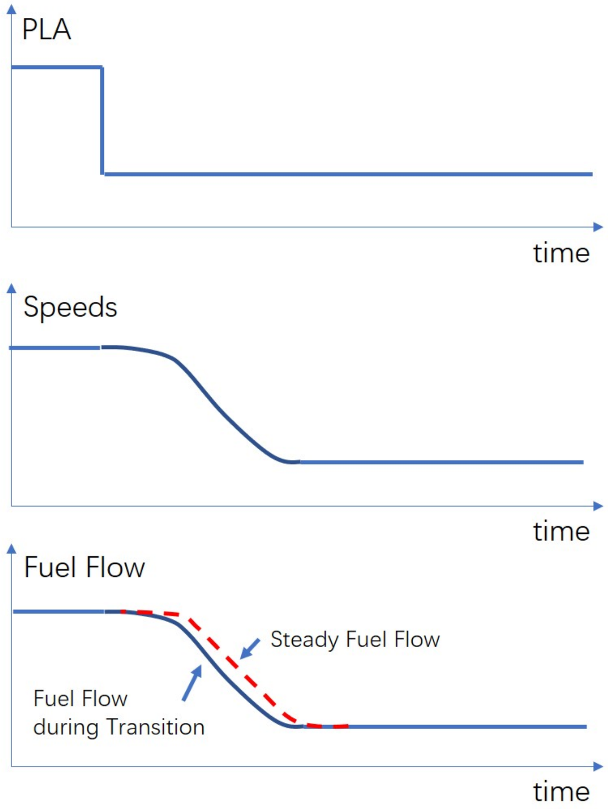

Figure 3 – Engine performance parameters versus time during rapid deceleration

3. Dynamic properties of the transition state

From the above analysis, it is clear that the aero-engine transition state can be roughly distinguished into two typical processes, acceleration and deceleration. Describing the transition state of an aero-engine is very complicated. The mathematical model to describe it should not only contain the start and end states, but also the variation process during the acceleration or deceleration. The transition state model of an engine mainly contains 3 basic dynamic equations.

3.1 Rotor dynamics - inertia effect

Rotor dynamics represents the simplest but most important dynamic behavior in an aero-engine.As shown in the figure 5, in the rotor dynamics model, two disks are used to represent the compressor and turbine, respectively, which are connected by a rigid shaft. The acceleration of the rigid body system (including the disks and rigid shafts) can be obtained from the dynamics equation

$$\dot{\omega} = \frac{Q_t - Q_c}{I} \tag{1}$$

In the formula, the symbol $\dot{\omega}$ represents the angular acceleration of the rigid system,$Q_t$represents the turbine torque,$Q_c$represents the compressor torque,Irepresents the mass moment of inertia of the rigid body system.

3.2 Pressure Dynamics - Mass Storage Effect

As shown in the figure 6, Aero engines contain numerous volume chambers,which are either large or small.all of which can store a certain mass of air or gas.These large chambers contain the combustion, compressor, turbine, and bypass flow paths, while the smaller chambers contain various air cavities. Since air/gas is a continuous medium. The mass storage effect in the volume causes the pressure and temperature inside the chamber to varies. Consider the simplified air-holding cavity shown in the figure 7. The rate of change of the mass of air (or) gas in the control body is

$$\dot{m} = \dot{m}_{in} - \dot{m}_{out} \tag{2}$$

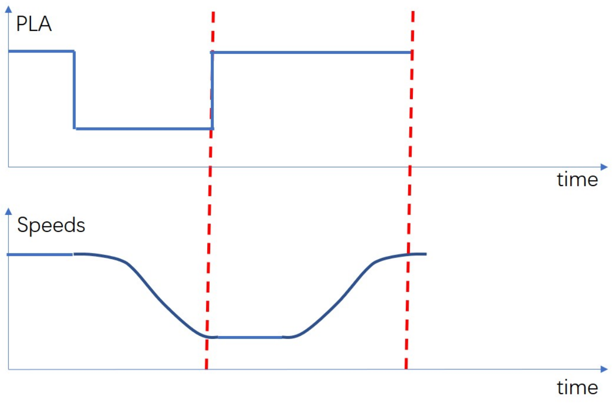

Figure 4 – The hot reslam or ‘Bodie’ manoeuvre

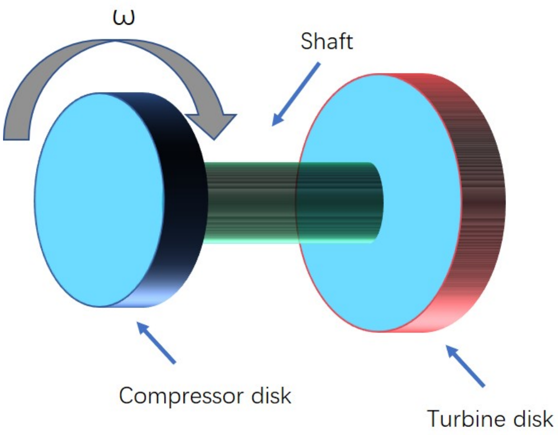

Figure 5 – Double-disc rotor dynamics mode

The air (or gas) in the volume is characterized by temperature T, pressure p and density ρ.then there are

$$\dot{p} = (\rho R)_0 \dot{T} + (\frac{RT}{V})_0 \dot{m} \tag{3}$$

where the subscript 0 means the nominal state point.$(\rho R)_0 \dot{T}$ is a small quantity relative to $(\frac{RT}{V})_0 \dot{m}$, so

$$\dot{p} \approx (\frac{RT}{V})_0 \dot{m} \tag{4}$$

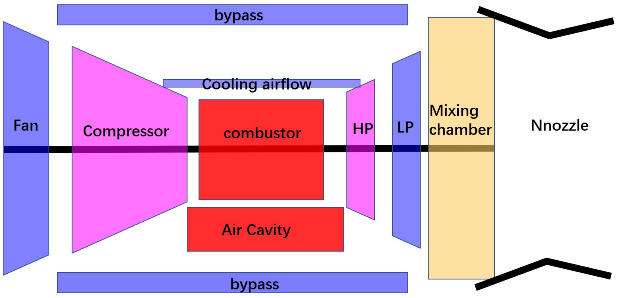

Figure 6 – Twin-shaft turbofan engine air and gas storage space

3.3 Temperature dynamics - energy storage effect

Aero engines have two types of temperature dynamics, one is the temperature change due to a direct change in the thermodynamic state of the air or gas in the volume. The other type is the temperature

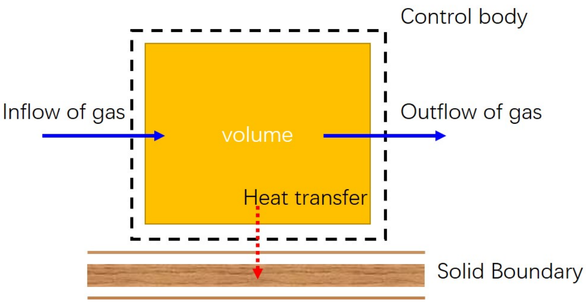

Figure 7 – Simplified model of gas volume

change caused by heat conduction between the metallic components at the hot end of the engine and the gas stream. A direct change in thermodynamic state is a change in pressure or temperature of the air or gas due to work done or consumed by the turbomachinery. The heating of the air/gas by chemical reactions in the combustion chamber can also lead to a change in the thermodynamic state. The temperature change directly caused by the thermodynamic effect is an order of magnitude faster than the time of the metal heating effect.

The expression of the temperature change rate of the control body is as follows.

$$\dot{T} = \left(\frac{RT}{C_v pv}\right)_0 (\dot{m}_{in} h_{in} - \dot{m}_{out} h_{out} + \dot{q}) + \left(\frac{RT^2}{pv}\right)_0 \dot{m} \tag{5}$$

4. Effects of transition states on components

As mentioned earlier, this paper classifies typical transition states and analyzes the dynamics characteristics during their variation. This section will focus on the analysis of the effect of transition states on the main components of the aero-engine in terms of aerodynamic and thermodynamic aspects.The main components analyzed in this section contain the compressor, combustion chamber, and turbine.

4.1 Effects on compressors

The effect of the transition state on the compression system is very complex. The compression system of a conventional turbofan engine can be divided into a fan and a high-pressure compressor. It is generally believed that the effect of rapid acceleration and deceleration transition states, on the high-pressure compressor is determined, as shown in the figure, the acceleration process makes the high-pressure compressor work above the steady-state operating line, while the deceleration process makes it work below the steady-state operating line ,as shown in the figure 9.

The effect of the transition state on the fan is a bit more complicated, because the high pressure and low pressure shaft speed changes are mismatched during the speed increase and decrease. Therefore, as shown in the figure 8, the transition state operating line and the steady state operating line of the fan appear to intersect. In the transition state, the remaining power from the turbine connected to the compression system determines the rate of variation of the shaft system speed.

4.2 Effects on combustor

The working condition of the combustor is mainly determined by two factors, one of which is the inlet air environment provided by the compressor, and the other is the amount of fuel supplied by the fuel nozzle. In the acceleration process, the fuel supply rapidly increases, the excess air coefficient in the combustion chamber rapidly decreases, if the fuel supply is too large, it may reach the fuel-rich flameout boundary and cause flameout. The deceleration process is just the opposite.

A diagram of the variation of the excess air coefficient with speed during acceleration can be seen in Figure 10.

In general, the first stage of the transition state occurs in the combustion chamber, and the change in the heat of the combustor to the air directly affects the operating state of the compressor and turbine.

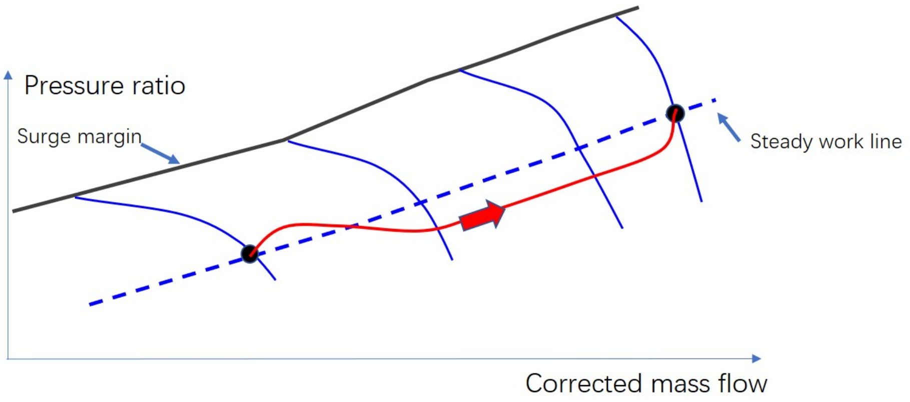

Figure 8 – Transition work line of fan during acceleration manoeuvre

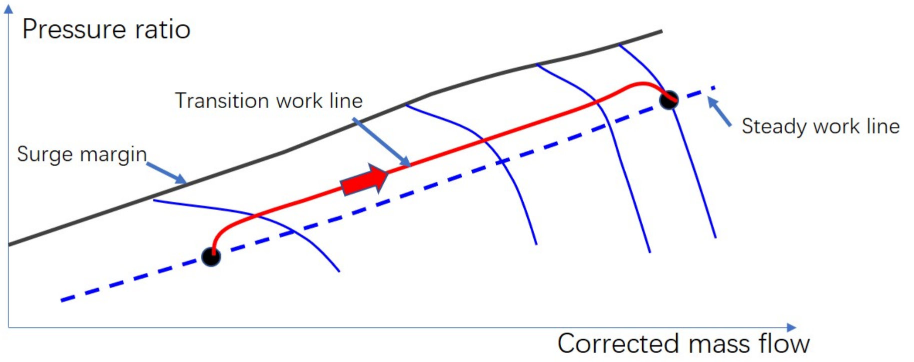

Figure 9 – Transition work line of compressor during acceleration manoeuvre

Therefore, the supply strategy for fuel flow in the transition state is often finalized after several rounds of analysis and iterations.

Changes in combustion efficiency due to sudden changes in fuel supply resulting in fluctuations in the combustion process should also be taken into account.

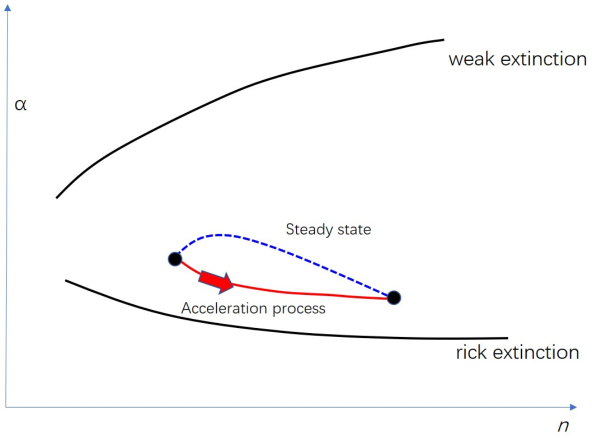

Figure 10 – excess air coefficient change curve during acceleration

4.3 Effects on turbine

The effects of the transition state are undoubtedly the most severe for the turbine. The transient flow with high time-varying characteristics provided by the compressor and combustor in the transition state will act directly on the turbine.

The turbine inlet is connected to the combustor outlet upstream, the inlet temperature distribution is not uniform, the highest temperature to lowest temperature ratio may reach the level of 2.0, and the incoming turbulence is highly variable, generally up to 3-10%, and may even reach 20%.

The pressure distribution is not uniform, while the non-constant and non-uniform nature of the flow is exacerbated by the injection of cooling gas from the turbine blades and end wall surfaces. Meanwhile, during the transition process, the blade tip clearance, the supply of cooling gas, and the transient of turbine inlet flow all directly affect the working condition of the turbine. Therefore the transition state characteristics of the turbine are difficult to provide by mechanistic analysis.

As Figure 11 gives the process of the turbine operating state on its performance graph for a typical acceleration condition. In the actual transition process of the turbine, the real condition is much more complicated than the description in the figure. Due to the complicated change process, the actual efficiency of the turbine differs significantly from the efficiency obtained from the steady-state performance experiment.

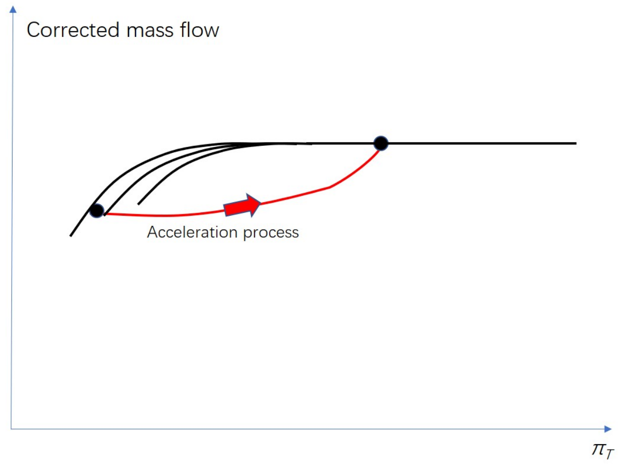

Figure 11 – Effect of transition state on turbine operating conditions

5. Transition state test construction analysis

By analyzing the transition states of the above types of aero engines, most of the aerodynamic thermal parameters change rate and rotational speed change rate in the transition state are first-order linear correlation, such as airflow pressure and airflow temperature. Some of the aerodynamic thermal parameters change rate and rotational speed change is second-order linear correlation, such as the temperature change of the magazine and blades. Based on the above study, the aerodynamic frequency domain range in the aero-engine is roughly divided, as shown in Figure 12.

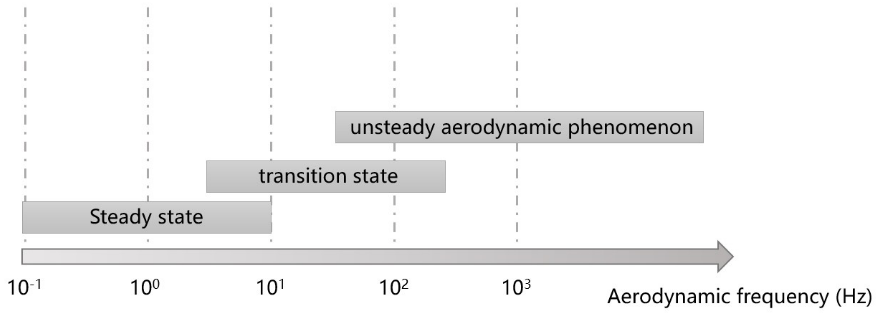

Figure 12 – Schematic diagram of the corresponding frequency range of each type of aerodynamic state

The range of aerodynamic frequencies in the transition state is roughly in the order of $10^1$and 102 hz. When conducting tests in the transition state, it is often necessary to make a rough estimate of the analysis frequency or sampling frequency, and this paper provides the recommended values of the sampling frequency as the following equation.

$$f_{sample} = 2.56(\frac{n_{max}}{60}) \tag{6}$$

n_{max}In the equation (6) is the maximum speed during the test, the unit is rpm.
Acceleration and deceleration performance tests were conducted for the transition state of a five-stage low-pressure turbine, and the schematic diagram of the five-stage low-pressure turbine can be seen in the figure 13. Steady-state and dynamic temperature and pressure test sections were set up at the inlet and outlet of the low-pressure turbine.Dynamic pressure is measured with kulite sensors and dynamic temperature is measured with 0.3mm thick thermocouple wire.

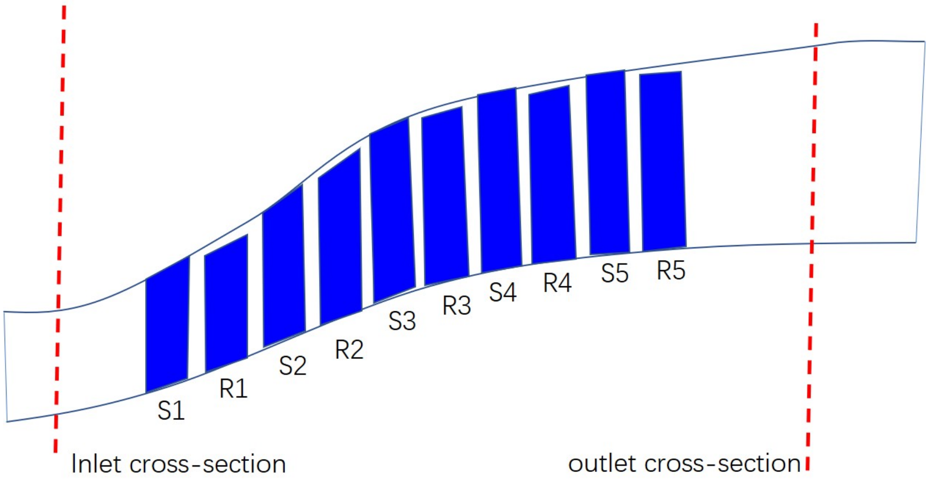

Figure 13 – 5 stage low pressure turbine schematic

In order to conduct the turbine transition state test, the inlet valve, heating system, dynamometer, and test system of the test facility were upgraded, as shown in Figure 14, which shows the pressure ratio change process of this five-stage turbine under the acceleration state.

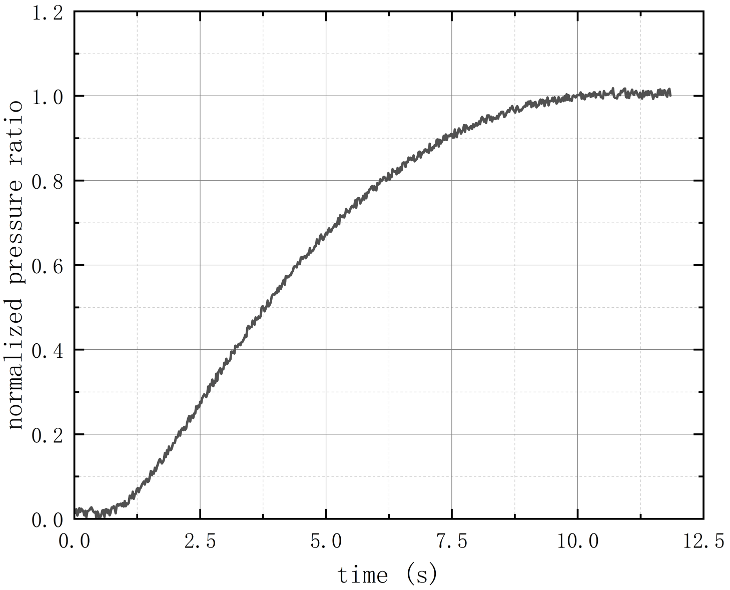

Figure 14 – Test results of pressure ratio variation in 5-stage turbine transition state

6. Conclusion

This paper discusses in detail the definition, characteristics and other aspects of transition states in aero engines, and the main conclusions are as follows.

1. although there are many types of aero-engine transition states, they can be broadly classified as acceleration and deceleration processes.
2. acute acceleration, acute deceleration and bodie processes are the three most important types of transition processes.
3. The processes of aero-engine transition states are described in detail.
4. the dynamics of the transition process is elaborated.
5. the effects of transition processes on the performance of the compressor, combustion chamber, and turbine are described in detail.
6. The relationship between the variation of pneumatic thermal parameters with rotational speed during the transition is discussed, and the recommended sampling frequency for the component transition state test is provided.
7. Typical test results for a five-stage turbine transition state are provided.

References

[1] Link C.Jaw and Jack D.Mattingly. *Aircraft Engine Controls design,system analysis,and health monitoring*. 1st edition, AIAA, 2009.

[2] Joachim Kurzke • Ian Halliwell. *Propulsion and Power An Exploration of Gas Turbine Performance Modeling*. 1st edition, Springer, 2018.

[3] Philip P. Walsh and Paul Fletcher. *Gas Turbine Performance*. 2nd edition, Blackwell science, 2004.

[4] Rolls-Royce. *The Jet Engine*. 1st edition, Rolls-Royce Plc, 1996.

[5] Bunker RS. Gas Turbine Heat Transfer: Ten Remaining Hot Gas Path Challenges*ASME Journal of Turbomachinery*, Vol. 129, No. 2, pp 193-201, 2007.

[6] McLean C, Camci C, Glezer B. Mainstream Aerodynamic Effects Due to Wheelspace Coolant Injection in a High-Pressure Turbine Stage: Part I - Aerodynamic Measurements in the Stationary Frame*ASME Journal of Turbomachinery*, Vol. 123, No. 4, pp 687-696, 2001.

[7] McLean C, Camci C, Glezer B. Mainstream Aerodynamic Effects Due to Wheelspace Coolant Injection in a High-Pressure Turbine Stage: Part II - Aerodynamic Measurements in the Rotational Frame.*ASME Journal of Turbomachinery*, Vol. 123, No. 4, pp 697-703, 2001.

[8] Gallier KD, Lawless PB, Fleeter S. Investigation of Seal Purge Flow Effects on the Hub Flow Field in a Turbine Stage Using Particle Image Velocimetry. *36th AIAA/ASME SAE/ASEE Joint Propulsion Conference & Exhibit*, Huntsville, USA: American Institute of Aeronautics and Astronautics,2002.

[9] Athavale MM, Steinetz BM, Hendricks RC. Gas Turbine Primary-Secondary Flowpath Interaction: Transient, Coupled Simulations and Comparison With Experiments. *35th AIAA/ASME SAE/ASEE Joint Propulsion Conference & Exhibit*,Salt Lake City, USA: American Institute of Aeronautics and Astronautics, 2001.

[10] Reid K, Denton J, Pullan G, et al. The Effect of Stator-Rotor Hub Sealing Flow on The Mainstream Aerodynamics of A Turbine. *Proceedings of ASME Turbo Expo 2006: Power for Land, Sea and Air*,Barcelona, Spain: American Society of Mechanical Engineers, 2006.

[11] Blanco ED, Hodson HP, Vazquez R. Effect of the Leakage Flows and the Upstream Platform Geometry on the Endwall Flows of a Turbine Cascade.*Journal of turbomachinery*, Vol. 133, No. 4, pp 42-49, 2009.

[12] Pau M, Paniagua G. Investigation of the Flow Field on a Transonic Turbine Nozzle Guide Vane with Rim Seal Cavity Flow Ejection. *Proceedings of ASME Turbo Expo 2009: Power for Land, Sea and Air. Orland*. Orland, USA: American Society of Mechanical Engineers, 2009.

[13] Schuepbach P, Abhari S, Rose, MG, Gier J. Sensitivity of Turbine Efficiency and Flow Structures to Varying Purge Flow.*Journal of Propulsion and Power*, Vol. 26, No. 1, pp 46-56, 2010.

[14] Schuepbach P, Abhari RS, Rose MG, et al. Effects of Suction and Injection Purge-Flow on the Secondary Flow Structures of a High-Work Turbine.*ASME Journal of Turbomachinery*, Vol.132, No.4, 021021, 2010.

[15] Bunker RS, Laskowski GM, Bailey JC, et al. An Investigation of Turbine Wheelspace Cooling Flow Interactions With a Transonic Hot Gas Path – Part I: Experimental Measurements.*ASME Journal of Turbomachinery*, Vol.133, No.4, 021015, 2011.

[16] Laskowski GM, Bunker RS, Bailey JC, et al. An Investigation of Turbine Wheelspace Cooling Flow In-

teractions With a Transonic Hot Gas Path – Part II: CFD Simulations.*ASME Journal of Turbomachinery*, Vol.133, No.10, 041020, 2011.

[17] Schrewe S, Werschnik H, Schiffer HP. Experimental Analysis of the Interaction Between Rim Seal and Main Annulus Flow in a Low Pressure Two Stage Axial Turbine.*ASME Journal of Turbomachinery*, Vol.135, No.9, 051003, 2013.

[18] Chilla M, Hodson HP, Newman D.Unsteady Interaction Between Annulus and Turbine Rim Seal Flows. *ASME Journal of Turbomachinery*, Vol.135, No.9, 051024, 2013.

[19] Regina K, Kalfas AI, Abhari RS.Experimental Investigation of Purge Flow Effects on a High Pressure Turbine Stage. *ASME Journal of Turbomachinery*, Vol.137, No.4, 041006, 2015.

[20] Jia W, Liu HX.Numerical investigation of the interaction between upstream cavity purge flow and main flow in low aspect ratio turbine cascade. *Chinese Journal of Aeronautics*, Vol.26, No.1,pp 85-93, 2013.

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