Experimental Study on Cold Start of Aeroengine at High Altitude

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ABSTRACT : *Through the analysis of exhaust gases from the combustion products of the aircraft engine, the variation patterns of each conventional combustion-generated substance are identified. By applying reverse engineering based on experimental data, the combustion conditions within the engine combustion chamber are reconstructed and correlated with the engine's operational parameters. Integrating real-time QAR data, this study systematically analyzes and summarizes the issues encountered, examines the observed phenomena, and identifies the root causes of the engine's start-up difficulties. In the actual start-up of high-altitude engines, ignition and fuel supply are initiated when the engine speed reaches 30%, which increases the air flow rate and correspondingly raises the fuel volume, thus maintaining the air-fuel ratio at a certain level.*

KEYWORDS *-cold start, aircraft engine, startup failure, testing*

I. INTRODUCTION

The primary challenges in starting an aircraft engine in a plateau environment include over-temperature, over-speed, extended start times, and reduced reliability. In plateau regions, the lower air density and atmospheric pressure result in decreased air mass flow rates, leading to diminished starter power. Consequently, the initial two stages of the starting process experience significantly prolonged durations [1]. During the final stage, the difficulty in compressing air necessitates greater compressor power to achieve the same energy output, resulting in insufficient turbine residual power, slower acceleration, and extended start times. Without appropriate measures, engines at plateau airports frequently encounter prolonged start times, accompanied by white smoke and flame emissions [2, 3]. Key parameters influencing engine start performance in plateau environments are atmospheric pressure, temperature, and density. As altitude increases, atmospheric pressure decreases, reducing the air mass entering the engine per unit time. This decrease lowers compressor efficiency and reduces the amount of compressed air entering the combustion chamber, leading to an imbalanced air-fuel ratio that becomes overly rich, potentially causing over-temperature conditions and damaging the turbine blades [4, 5]. For aero gas turbine engines, the increased power demand on the compressor during the start process, coupled with insufficient residual power, results in slow engine acceleration and may prevent it from reaching idle speed.

II. ANALYSIS OF ENGINE STARTUP FAILURE

The slow increase in engine speed and the excessively long start-up time need to be studied from the perspective of turbine power. Insufficient turbine power before the starter disengages or after it disengages, compared to the power consumed by engine acceleration, can both lead to difficulties in starting. There are relatively more reasons for incomplete combustion, such as poor fuel atomization quality, poor fuel vaporization quality, and fuel nozzle malfunctions. In high-altitude environments, an increase in the back pressure of the combustion chamber or low injection pressure can both affect the quality of fuel atomization.

With the use of the starter, its performance degradation can also lead to insufficient power. The start hang mainly occurs under cold start conditions in winter at high altitudes. Therefore, the method of comparing the time it takes for the starter alone to accelerate the engine to the same speed under cold start conditions in winter at high altitudes and on plains was adopted for verification. Through extensive QAR data analysis, it was found that it takes about 15 seconds on the plain and about 25 seconds at high altitudes. The moment of inertia of the engine is smaller under high-altitude conditions, and the power required by the starter to accelerate to the same speed is also smaller. Because the air density is greater on the plain than at high altitudes, it is more difficult to compress, and more power is consumed to accelerate to the same speed. However, the acceleration time at high altitudes is longer, indicating a decrease in starter power.

III. THE DESIGN OF THE EXPERIMENTAL SCHEME

The experiment requires the real-time collection of exhaust gas when the aircraft engine starts. However, the collection and analysis of aircraft engine exhaust gas is technically challenging, with complex equipment structures, high measurement costs, and certain risks. This experiment uses a professional exhaust gas detection device, the German MRU VARIO PLUS industrial gas continuous analyzer, as shown in Figure 1. In the face of the complex environment of high temperature and high speed of the aircraft engine tailpipe, this exhaust gas detection device can still complete the collection work well. The probe of the detection device is made of high-temperature resistant materials and has good performance. The exhaust gas detection device is paired and connected with a computer software via Bluetooth, which can transmit and receive test data in real time and archive them.

Fig.1 MRU VARIO PLUS Continuous Analyzer

The MRU VARIO PLUS is composed of a high-definition LCD screen, data storage, efficient Peltier cooler, built-in high-speed printer, transmission cable, high-dust sampling probe handle, etc. The analysis detector has the characteristics of compact instrument design, light weight, portability, and high precision, which is suitable for the use of this experiment. The installation of the exhaust gas detection equipment must be conducted directly on the engine body. Designing the fixation and layout of the sensor is a critical consideration for this experiment. The specific principles guiding the design and installation are as follows:

1. This test is an in-wing test, which means it cannot compromise the integrity of the engine. As an aviation product, any modifications or additions to the engine and its specialized test equipment must comply with airworthiness regulations to ensure continued airworthiness.

2. Safety concerns must be prioritized during the installation process. This includes evaluating the installation forces, selecting appropriate positions, and ensuring no unexpected issues arise during testing. Additionally, it is crucial to verify that the aerodynamic forces acting on the test probe during aircraft start-up do not exceed its structural limits.

3. After thoroughly considering all requirements, the clip thickness is designed to be 10mm, meeting airworthiness standards. The detailed design of the clip is illustrated in Figure 2.

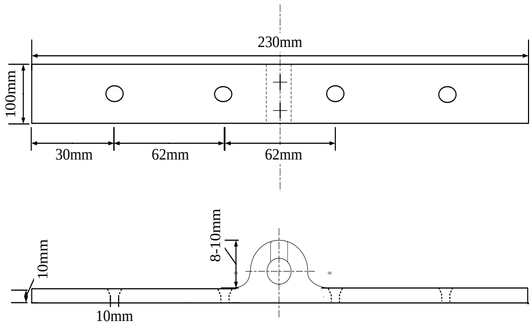


Fig.2 The design of the clamping piece

Fix the tail gas detection equipment probe on the engine pylon with the fixed clips. To avoid affecting the transmission of the detection equipment conduit, the sensing line of the detection head is wired from back to front. According to the previous on-site measurement in the hangar, it was found that the transmission distance was relatively long, so the length of the conduit was selected as 5.0 meters.

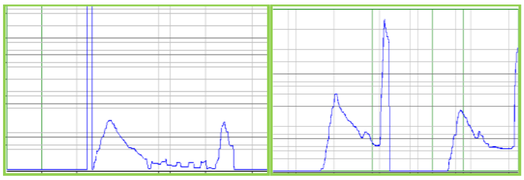
Step 1: This experiment selects Gongga Airport, located at an altitude of 3,600 meters, as the test site. Among several pre-selected aircraft that operate in high-altitude plateau regions, those with well-maintained and stable engines are chosen for the test. One engine has undergone technical upgrades, while the other remains unmodified. The aircraft engines must have sufficient cold-soak time, and the external atmospheric conditions must meet the requirements for pre-flight start-up in high-altitude plateau environments.

Step 2: According to the installation plan, the exhaust gas detection probes are securely fixed to the engine pylon using clips. The exhaust conduits are routed from back to front and secured with metal tape. The exhaust gas detection equipment box is placed in a safe area beneath the engine. In the ground safety zone, the computer software is activated and wirelessly connected to the detection equipment to ensure reliable operation of both hardware and software.

Step 3: After completing all preparatory work, the corresponding engines are started at idle speed, maintaining clear communication between the cockpit and the ground team. The two engines used in the test are started separately, and real-time data collection is performed using a continuous analyzer to determine the applicability of the plan in high-altitude plateau conditions. Relevant QAR data and exhaust gas collection data are recorded and analyzed to evaluate the feasibility of the proposed approach.

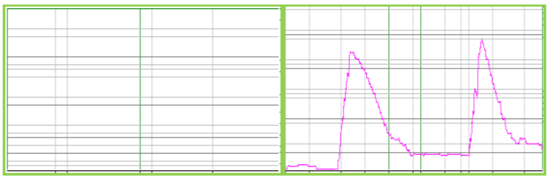
IV. DATA COLLECTION AND ANALYSIS

In this test, idle start-up tests were conducted on the left and right engines of the same aircraft respectively, and both were the first start-ups. During the data collection process, the exhaust gas of the engine was collected in this test, and the composition of the exhaust gas was analyzed and relevant parameters were recorded.



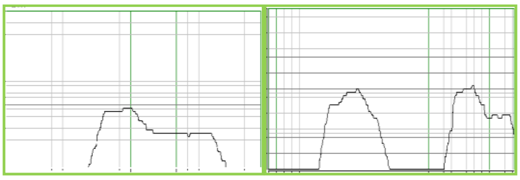
(a) Right Engine One Startup (b) Left Engine Two Startup

Fig.3 CO Trend Chart



(a) Right Engine One Startup (b) Left Engine Two Startup

Fig.4 CH4 Trend Chart



(a) Right Engine One Startup (b) Left Engine Two Startup

Fig.5 CO2 Trend Chart

The real-time engine monitoring data of the QAR for this test are shown in Figures 3, 4 and 5. The right engine is the upgraded CFM56-5B engine. As the engine speed reaches 30%, the engine starts to ignite and supply fuel, and the fuel flow rate shows a peak before rising slowly. When the speed reaches 50%, the starter disengages, and the fuel flow rate rises for a period of time before the fuel supply decreases. The exhaust temperature gradually increases and remains at a certain level. At this point, the speed stabilizes at 60%, and the engine reaches idle state. The cold start of the engine is successful, and this start process is a normal one. The left engine is the un-upgraded CFM56-5B engine. During the first start of the engine, there is a clear flame at the tailpipe outlet and white smoke, with a popping sound. It is initially judged to be the product of incomplete combustion. Then, the engine is shut down and cold-turned for a period of time before starting again. This time it is a hot start, and the second start is successful, with normal phenomena at the engine tail.

Tests show that the cold start time of the engine after technical upgrades is similar to the hot start time of the engine under normal circumstances. Under normal conditions, the engine ignites the mixture, and the ECU controls the ignition and fuel supply logic, mainly monitoring the EGT. If the EGT does not rise by 42℃ within 15 seconds, the ECU determines that the engine ignition has failed and automatically cuts off the fuel supply and stops the ignition, resulting in a failed engine start. The upgraded engine can reach the required level within the normal time, and it has made significant improvements in the fuel supply logic control. At lower temperatures, the engine starts to ignite and supply fuel, with a larger fuel supply. During the initial stage of about 5 seconds, the complete combustion products are generated, and the content increases, enabling the engine to reach the ideal EGT temperature and start normally. On the other hand, the production of by-products, namely C and H compounds, indicates their complete combustion. It can be seen that the software upgrade of the engine has changed the ignition and fuel supply rules of the engine, resulting in significant changes in the engine exhaust and hydrocarbons. Therefore, it can be determined that the white smoke is hydrocarbons. The formation of smoke is mainly due to physical factors such as the injection, evaporation and blending of fuel. The formation area of smoke is in the rich fuel zone, that is, the recirculation zone near the fuel nozzle. The high temperature, low oxygen content and rich fuel in this area lead to the generation of smoke. In addition, the main influencing factors of smoke formation include the combustion chamber pressure, the type of fuel and the atomization and vaporization quality of the fuel.

Considering the sudden increase and the appearance of hydrocarbons during the test process, which are caused by incomplete fuel combustion, the degree of complete combustion in the combustion chamber is measured by combustion efficiency. The fundamental reason for the long cold start time of the left engine is the relatively low combustion efficiency. A low combustion efficiency is often unacceptable, and civil aviation engines are required to have a combustion efficiency greater than 90% within the normal operating range. The combustion of the fuel-air mixture is a complex physical and chemical change process. It involves the atomization and evaporation of fuel, the vaporization of fuel and its mixing with air, the ignition of the formed combustible mixture, and then the chemical reaction of oxidation. Through the research on the exhaust gas test during the cold start of the engine at high altitudes, the incomplete combustion of fuel during the cold start process of the engine was obtained. It was clarified that the main components of the white smoke during the cold start process of the engine are CO and hydrocarbons. Through the discussion and research of the test, it was verified that there is a problem of poor atomization and vaporization of fuel during the cold start of the engine at high altitudes.

V. CONCLUSION

Real-time exhaust gas tests were conducted on the combustion products during the cold start of engines at high-altitude airports. By combining real-time QAR data and exhaust gas component test results, it was first determined that the white smoke during the cold start of engines is mainly composed of hydrocarbons and its formation mechanism. Finally, it was verified that there is a problem of poor fuel atomization and vaporization during the cold start of engines at high altitudes. The tests showed that in winter at high-altitude airports, the fuel temperature is low, the fuel viscosity is high, the pressure is relatively low, and the fuel flow rate is small. At the same time, the gas density is small, the liquid fragmentation is small, the fuel vaporization is poor, and more hydrocarbons are produced.

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