

Verification of High Altitude Performance and Characteristics for HF120 Turbofan Engine

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ABSTRACT

The HF120 turbofan engine co-developed with General Electric Company was tested to verify its high altitude characteristics. Ownership of the tests was cooperatively shared between General Electric Company and Honda with General Electric Company leading the tests at the Altitude Test Facility and Honda leading the tests on the Flying Test Bed. A small business jet aircraft modified to replace an engine on one side with an HF120 turbofan engine was used for the Flying Test Bed. A data measurement system that can handle the large amounts of data acquired during flight tests was installed inside the aircraft to verify the engine conditions comprehensively.

The high altitude characteristics required for aircraft engines were verified from multiple aspects by taking advantages of the two different types of test environments of Altitude Test Facility and Flying Test Bed.

The combination of performance test data and engine model simulation verified that overall steady state performance meets the requirements throughout the engine operating envelope. Acceleration and deceleration characteristics have been verified to meet the requirements. Surge and stall characteristics have been verified to secure the required surge margin. The air start envelope has been verified through numerous air start demonstrations.

1. Introduction

The high altitude region where an aircraft engine can operate is defined as the operating envelope using pressure altitude and Mach number. Table 1 shows the minimum and maximum range of the HF120 turbofan engine (HF120) flight pressure altitude, Mach number, atmospheric pressure and atmospheric temperature. The normal operation of the engine under such atmospheric conditions has been demonstrated by testing. The Altitude Test Facility (ATF) simulates high altitude conditions at a ground test facility while the Flying Test Bed (FTB) lets an engine installed in a real aircraft perform testing at high altitude flight conditions. This paper provides a description of how the HF120's high altitude characteristics were verified using these facilities.

Table 1 HF120 operating range

	Min.*	Max.*
Pressure altitude (ft)	-1000	46000
Mach number (-)	0	0.85
Atmospheric pressure (kPa)	14.1	105.0
Atmospheric temperature (°C)	-77	55

* Min. and max. actual limitations are defined by operating envelope.

2. Characteristics of ATF and FTB

Figure 1 shows the HF120 installed in the ATF owned by General Electric Company (GE)⁽¹⁾. The ATF is designed to simulate high altitude atmospheric conditions

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with accuracy and stability. As a ground test facility, the ATF provides a relatively high degree of freedom for instrumentation and other related equipment. Furthermore, the ability to directly measure thrust, which is difficult using the FTB, and the absence of constraints such as test time and weather make it possible to acquire detailed data under varied conditions.

However, the requirements for an ATF are demanding, needing a large-scale facility including equipment to cool and depressurize the copious amount of engine air inflow. For this reason, only a handful of engine manufacturers have ATFs.

Figure 2 shows the FTB with the HF120 installed. The FTB has a test engine installed on an existing aircraft, which can be tested under actual flight conditions. In addition to testing with aircraft movement, other items to be evaluated uniquely in FTB tests include vibration measurement during landing.

When performing an FTB test, partial alteration of the airframe is necessary to install the test engine. Also, atmospheric conditions at high altitude change occasionally, requiring certain flexibility in the test conditions.

HF120 high altitude characteristics were verified by utilizing the features of these two different test facilities that complement each other.

The ATF tests were led by GE and performed at the GE-owned ATF. Honda engineers provided their technical support on site.

The FTB tests were led by Honda and performed in cooperation with Atlantic Aero, Inc. (AA) in the United

States. The test vehicle used was a small business jet aircraft with an engine on one side replaced by the HF120. The aircraft alteration plan was developed by Honda, carried out by AA, and an experimental Airworthiness Certificate was obtained. GE was responsible for supporting engine assembly and part of the instrumentation.

Collaboration with these companies started in the planning phase and continued while ATF and FTB tests were performed. Data acquired during these tests was shared between GE and Honda and analyzed in coordination between the U.S. and Japan.

3. Test Items

Table 2 shows the list of evaluation items for verifying high altitude characteristics. Among the evaluated items were overall engine high altitude characteristics as well as subsystems relating to such as fuel, lubrication and vibration. A broad range of items were tested.

This chapter focuses on overall engine high altitude characteristics and describes some key points in the overview and technical assessment of each item.

3.1. Overall Steady State Performance, Acceleration and Deceleration

Engine performance during steady state flight conditions were evaluated using certain thrust and fuel consumption parameters. The evaluation not only covered the overall steady state performance but also included component characteristics such as the compressor, turbine and combustor.

For acceleration and deceleration, parameters such as acceleration and deceleration time, controllability, surge and stall, and lean blowout margin were evaluated. Surge and stall, in this context, refers to an unstable phenomenon of airflow passing through the compressor.

As examples of overall steady state performance tests, surge and stall tests are used to describe the selection method of the test points.

Individual characteristics of the ATF and FTB were taken into account in selecting test points, and each evaluation item was technically reviewed. Fundamentally, detailed and extensive amounts of data were collected by ATF tests, then major points at actual flight conditions were validated, and items unique to FTB tests were evaluated by subsequent FTB testing.

Figure 3 shows the HF120 operating envelope and representative test points used in evaluating overall steady state performance and surge and stall characteristics.

3.2. Windmill and High Altitude Air Start

Windmill refers to the condition of shaft rotation triggered by inflow aerodynamic forces while the engine is not operating. Since the rotating shaft is kept at a low speed under this condition compared to normal operation, lubrication and shaft vibration were evaluated under such



Fig. 1 ATF test setup and HF120

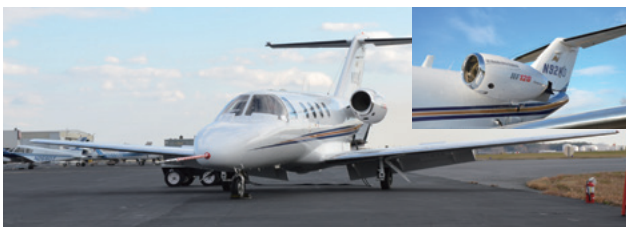


Fig. 2 FTB and HF120

Table 2 Evaluation items

Category	Evaluation item
Overall engine characteristics	Performance
	Acceleration and deceleration time
	Controllability
	Surge and stall margin
	Lean blowout margin
	Windmill
	Air start
	Maneuver (FTB only)
Sub systems	Fuel system
	Control system
	Start system
	Lubrication system
	Secondary air system
	Thermal system
	Vibration and dynamics

circumstances.

High altitude air start testing is intended to verify the envelope where an aircraft engine can restart at high altitude conditions. The envelope is bound by altitude and Mach number. Figure 4 shows test points and air start envelopes for the high altitude air start test. HF120 high altitude air start, as indicated in this figure, can be defined by three types of envelope: starter-assisted air start (SAAS) envelope, steady state windmill (SSWM) envelope, and quick windmill relight (QWRL) envelope.

3.3. Maneuver

Maneuver here refers to aircraft behavior and is evaluated in flight tests under various conditions such as attitude change, acceleration change and rolling pitch and

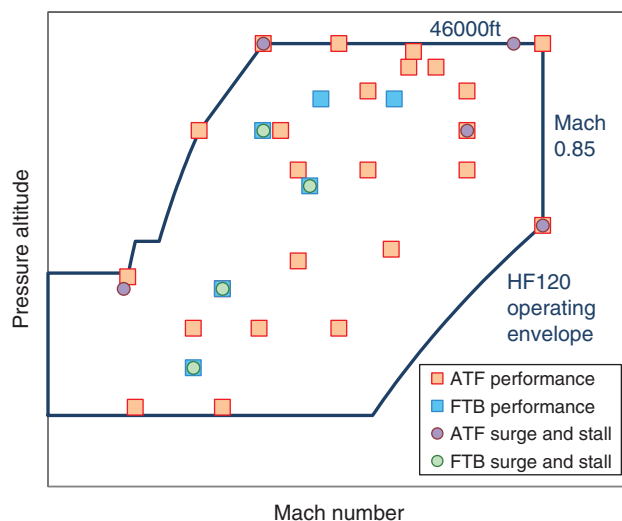


Fig. 3 HF120 operating envelope and test points

yaw fluctuation. Items being evaluated include lubrication function and vibration properties. In addition, disturbance from engine inlet air and its impact on overall steady state performance and acceleration and deceleration characteristics were also tested while flying with different angles of attack or angles of sideslip relative to the aircraft flying direction.

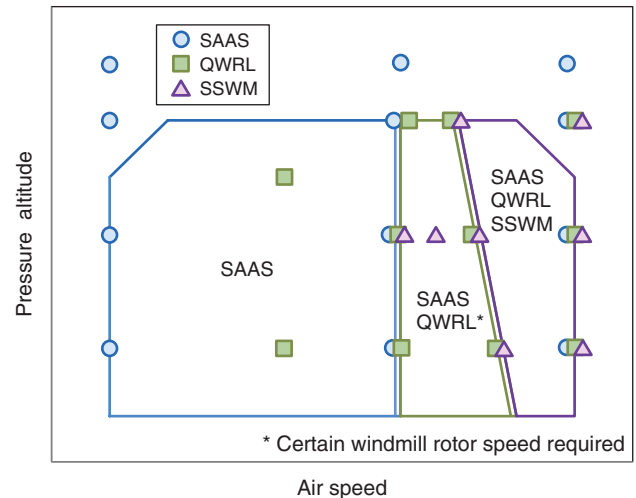


Fig. 4 HF120 air start test points and envelope

4. Test Facility and Operation

This section reviews the FTB test facility and test operation led and executed by Honda.

4.1. Data Measurement System

An instrumentation system was developed to measure various engine and airframe data with high precision in order to carry out the FTB tests.

Among the engine parameters measured were the temperatures, the pressures at representative positions, and the rotating speeds. In addition, high speed data sampling equipment to determine the vibrations and to detect any minor compressor stalls was installed as well as a system capable of measuring the clearance between rotor and casing, and bearing thrust loading.

To measure aircraft parameters, a boom installed on the nose of the aircraft measured flight conditions while a gyroscope installed inside the aircraft provided aircraft angle and angular velocity.

The items accumulated through this measurement system included over 400 channels in total, and all equipment including necessary instrumentation was installed inside the small business jet aircraft. The aircraft was extensively modified to accommodate the associated instrumentation layout and sensor signal routing. When carrying out this modification, aircraft cabin volume, electric power and

payload limitations were reviewed. Figure 5 shows the FTB data measurement system schematic.

Additionally, a video camera was mounted to monitor and record engine inlet external appearance in preparation for potential foreign object ingestion during flight testing (Fig. 6).

4.2. Control System

Figure 7 shows the FTB control system schematic. The HF120 Engine Control Unit (ECU) installed in the aft cargo room is a digital unit that controls fuel flow by receiving input values from engine sensors, various aircraft data and thrust lever angle (TLA) signals from the aircraft, and is a redundant system. The ECU can also detect engine and sensor malfunctions, and transmit data to the aircraft to indicate the engine condition. This data communication employs the Aeronautical Radio, Incorporated 429 (ARINC429) standard. In addition, as a backup for the ARINC communication system, the capability to output engine speed, temperature and oil pressure from the ECU analog circuit to the cockpit was provided.

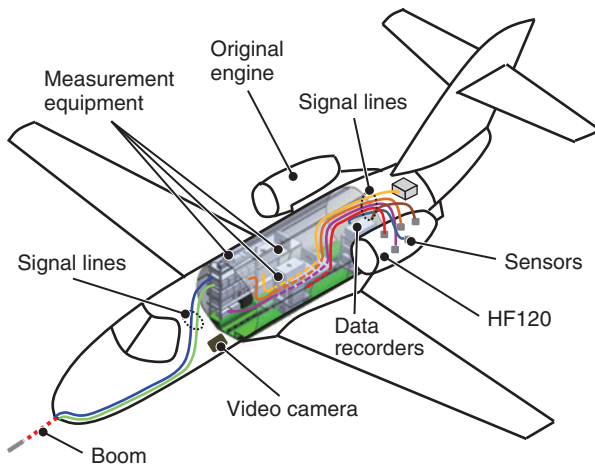


Fig. 5 FTB measurement system



Fig. 6 Engine monitoring camera view

TLA signals that belong to a different system from ARINC429 are recognized by the ECU via a Rotary Variable Differential Transformer (RVDT).

Moreover, the ECU has a Controller Area Network (CAN) data communication capability installed in it, and can input as well as output ECU internal parameters. Data from over 400 channels can be recorded at a high sampling rate when the Data Acquisition Panel (DAP) computer used in development is connected to the ECU via CAN communication. Also, ECU internal control settings can be overridden in real time during engine operation. This process is called adjustment by which testing under various control settings can effectively be applied without engine shutdown or ECU resetting.

The FTB had a computer called Interface PC installed in the cabin to connect the HF120 ECU to existing aircraft systems. The Interface PC was configured to mutually convert, send and receive aircraft data and ECU data.

In addition, the system also had information such as engine bleed level and landing gear weight-on-wheels (WOW) converted into the ARINC429 format by the Interface PC, so that it could be transmitted to the ECU.

4.3. Engine Mount and External Loading Simulation System

4.3.1. Engine mount

In order to switch the existing engine to the HF120, a new engine mount was manufactured and evaluated.

One of the key requirements for the engine mount to comply with is no engine separation under the maximum expected loads. The types of loads to be reviewed are the maximum impact load generated by loss of a fan blade, fatigue load generated by windmill after loss of a fan blade, and acceleration-induced load during maneuver testing. The engine dynamics model was used to evaluate the engine mount strength under these loading conditions, and it was analytically demonstrated that the engine would not be separated under any expected loading conditions.

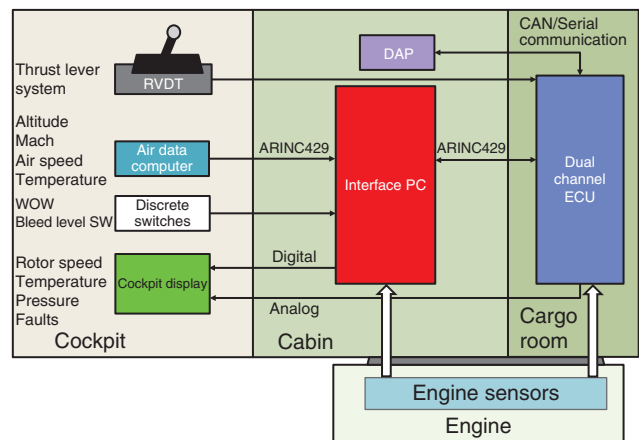


Fig. 7 HF120 FTB control system schematic

4.3.2. Fuel system

Because the existing fuel delivery system did not meet certain HF120 requirements, certain fuel piping and pumps in the FTB were replaced with units conforming to the HF120. This modification provided an independent fuel delivery system for both right and left sides, and the capability to install two engines having different fuel delivery requirements on a single aircraft.

4.3.3. External load simulation system

High pressure bleed air from the compressor is used for cabin pressurization and anti-icing systems when operating a business jet aircraft. Figure 8 shows the bleed air system configured to simulate this condition.

Electric power for instruments, air conditioners and electric lights is extracted from a generator mounted on the engine. This extracted electric power was regulated by variable load bank equipment during FTB testing. The load bank equipment was placed in the aft cargo room and structured to prevent overtemperature during operation by a cooling duct located on the side of the aircraft. Figure 9 shows photos of the variable load bank equipment.

Since the bleed air and the extracted electric power can induce external loads on the engines and affect engine characteristics, they are set as part of the test conditions.

By executing what was described in Sections 4.1

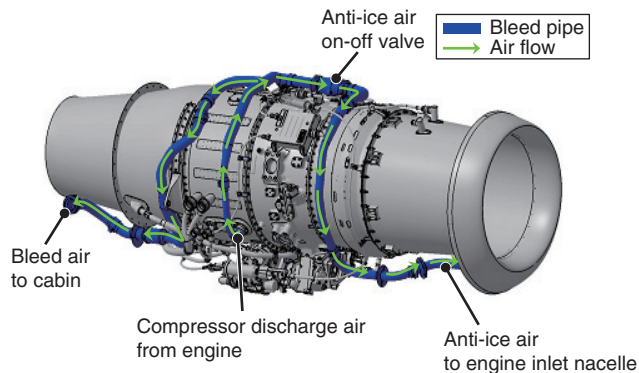


Fig. 8 Bleed air system

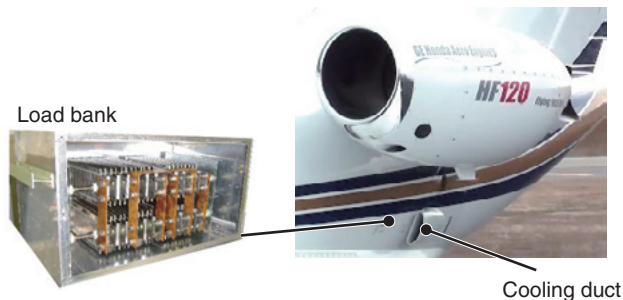


Fig. 9 Load bank and cooling duct

through 4.3, a flight testing system was formulated which efficiently evaluated the engine characteristics at multiple flight conditions from diverse perspectives.

4.4. Operation during Flight Test

Two flight test engineers and two pilots were on board during the FTB tests. The engineers constantly monitored the engine data, aircraft data and control data. The engineers gave instructions to initiate the tests one by one while communicating with the pilots through an intercom system, then executed the flight tests accurately and effectively by assessing the test results.

5. Verification Results of High Altitude Characteristics

Four examples of verified HF120 high altitude characteristics are provided as below.

5.1. Verification of Overall Steady State Performance

Overall steady state performance contributes a great deal to aircraft performance during takeoff, climb, cruise, descent and landing throughout the entire operating envelope.

In order to evaluate a wide range of conditions with efficiency, characteristics of each engine component, such as the compressor or the turbine, were used to formulate a numerical computational model (hereinafter referred to as the model) to derive overall steady state performance. The effects of sensors or introduced parts were taken into account. The comparison between test results from typical flight conditions and values derived from the model validated the model.

Figure 10 shows the model validation process. If any difference is found through comparison of the test results with model derived values, the model will be adjusted until the discrepancy falls within an allowable tolerance. Major parameters used here are low pressure shaft speed (N1), high pressure shaft speed (N2), fuel flow rate, and interstage turbine temperature (ITT).

In order to validate the model, the impacts of changes made to test the engines were examined. These effects are primarily attributable to variation of components in the test engine, as compared to product engines, and sensor(s) installed inside the engine. These effects were derived from component test results or computational fluid dynamics analysis results.

A production engine model was obtained by comparing the model derived values with the test results, and then removing the test engine specific effects from the model.

Figure 11 shows model derived values (solid lines) and ATF test results (plotted points). As this chart displays multiple data with different test conditions, estimated values and test results were found to be consistent.

In this manner, overall steady state performance has been confirmed to meet the requirements throughout the

operating envelope by using the model verified by high altitude test results.

5.2. Acceleration and Deceleration Response Test

The acceleration and deceleration response testing was performed by varying altitude, Mach number and engine external loading conditions. For example, rapid acceleration is needed to generate the thrust demanded by pilot in circumstances such as a go-around.

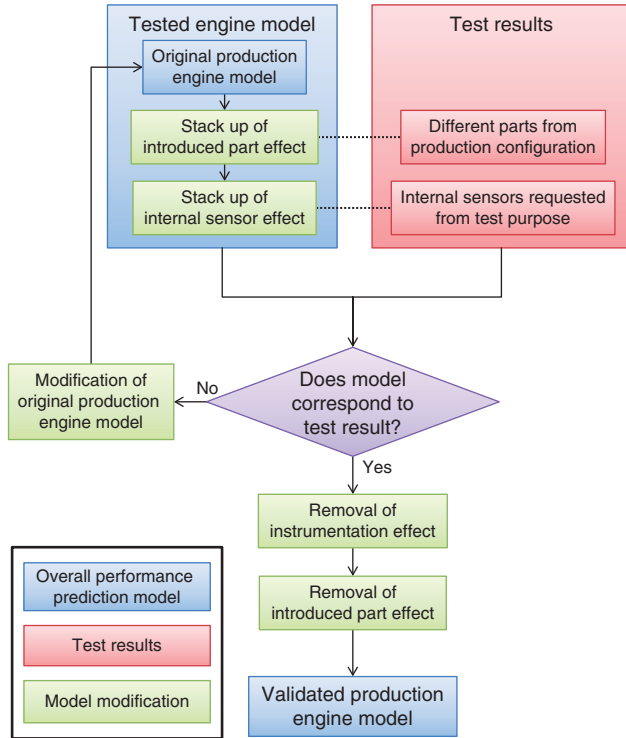


Fig. 10 Validation process of performance prediction model

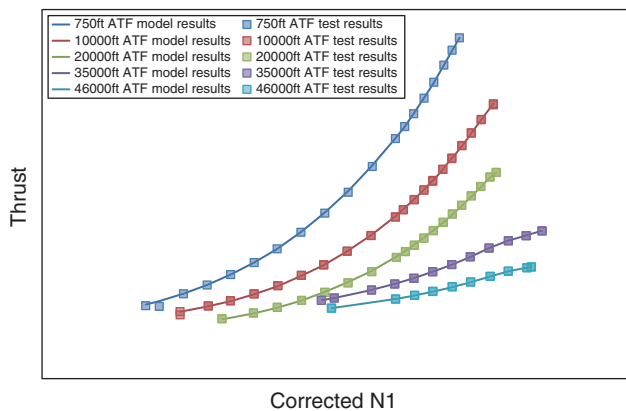


Fig. 11 Comparison between ATF model results and ATF test results

Figure 12 shows an example of engine behavior during quick acceleration. The acceleration response test focused on evaluating whether the acceleration time and the ITT values fall within the requirements while the deceleration response test focused on evaluating deceleration time. With other evaluations, it was demonstrated that both acceleration and deceleration meet the requirements within the operating envelope shown in Fig. 3.

5.3. Surge and Stall Test

A testing to check compressor surge margin was performed. This section describes the surge test for the high-pressure compressor. In order to confirm the surge margin during normal acceleration, the fuel flow command during acceleration was set higher than usual to intentionally trigger compressor surge. The higher fuel flow was set especially at the target engine speed so as to prevent engine overtemperature.

Figure 13 shows an example of a surge that actually occurred. Rapid decrease in high pressure compressor exit pressure (P3) indicates that a surge occurred.

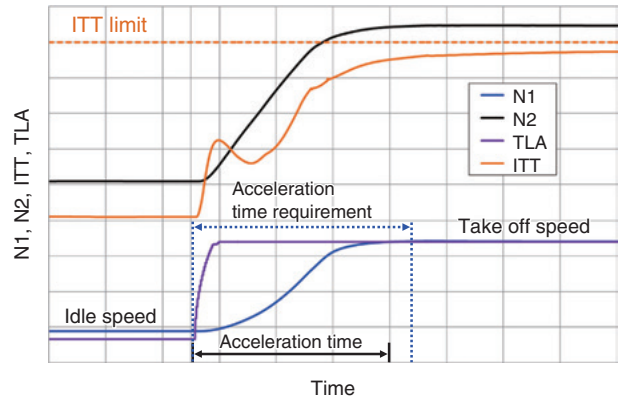


Fig. 12 Quick acceleration from idle

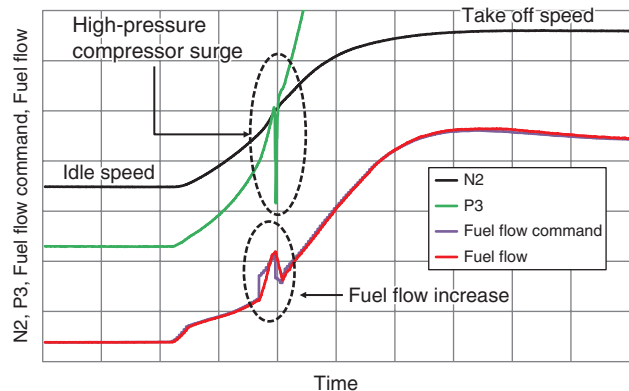


Fig. 13 High-pressure compressor surge test

Figure 14 shows the simple schematic of the high-pressure compressor surge line and the operating line. While the operating line during acceleration tends to get close to the surge line from the steady state operation line as indicated by arrows (A) and (B), it eventually reaches the takeoff running point. In addition, the higher the acceleration rate becomes, the closer the operating line moves to the surge line. In this figure, (A) indicates normal rapid acceleration operation which corresponding to Fig. 12, carrying a certain margin relative to the surge line by component test data. On the other hand, (B) represents the operating line when fuel flow was intentionally enriched to trigger a surge, and this surge was observed after the operating line surpassed the surge line by component testing.

The engine surge line was identified by varying engine inlet ambient conditions, the speed region and other parameters. By comparing this line with the operating line during normal acceleration, and then reviewing operating line shifts as a function of flight conditions, external loading conditions and others, it was verified that the HF120 has sufficient surge margin.

5.4. High Altitude Air Start Test

High altitude air start testing was executed by varying altitude and Mach number. As described in Chapter 3, three types of engine start sequence were defined.

First, Fig. 15 shows SAAS. The N2 threshold indicates the lowest speed limit capable of commanding fuel flow. In this figure, the pre-start N2 is less than the threshold and the starter is necessary for air start. Afterwards, the starter assist raises N2. Once N2 reaches a certain speed, relight provides ITT increase, which is followed by subsequent N2 increase, finally reaching steady state idle conditions. During this period, ITT limit is not exceeded and the air start is completed in a normal manner.

Next, Fig. 16 shows SSWM. It is a steady state windmill condition prior to start, with ITT and N2 statically determined. Since N2 is higher than the threshold, the subsequent relight is successful without relying on the

starter. With no ITT overtemperature observed, the air start is finally completed.

Lastly, Fig. 17 shows QWRL. As shown in the figure, air start was initiated within a short time after engine shutdown operation. Hence, N2 exceeds the threshold, similar to SSWM, and no starter assist is necessary. Also in

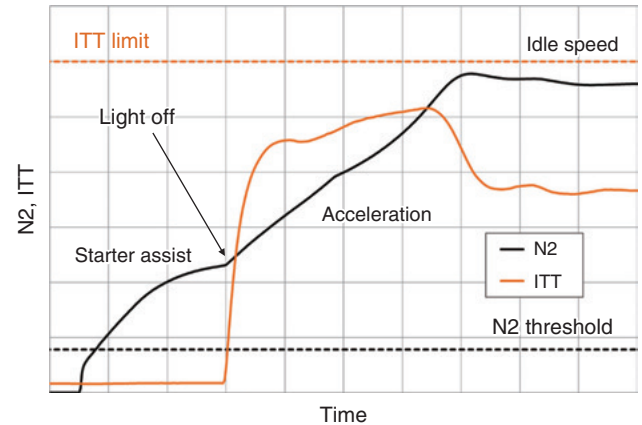


Fig. 15 SAAS

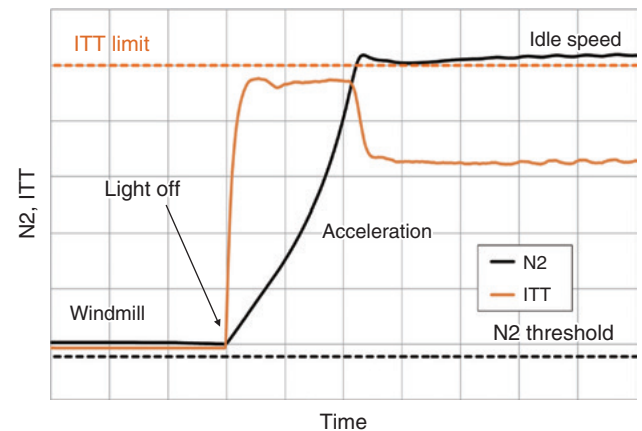


Fig. 16 SSWM

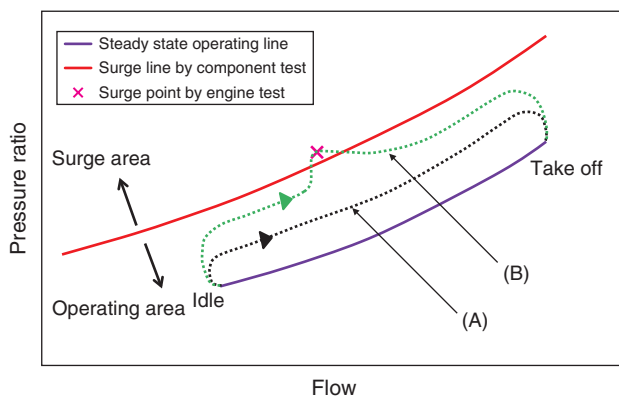


Fig. 14 Simple schematic of high-pressure compressor surge and operating line

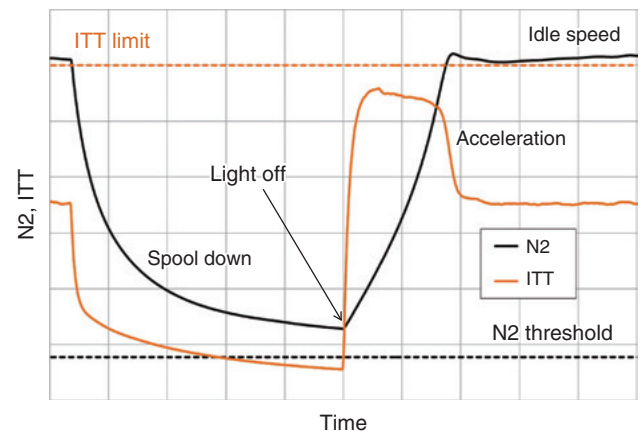


Fig. 17 QWRL

this case, no ITT overtemperature is observed, and the air start is finally completed.

ATF and FTB tests were performed over 300 times in total combined to validate the air start envelope shown by solid lines in Fig. 4.

6. Conclusion

HF120 high altitude characteristics were tested by employing an ATF simulating high altitude conditions using a ground test facility and an FTB capable of flight tests. The FTB tests had the engine on one side of a small business jet aircraft replaced by the HF120, and the developed flight testing system capable of measuring data of over 800 channels in order to evaluate multiple test items. The ATF and FTB test results were used to validate the high altitude characteristics of the HF120 within the operating envelope.

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- (1) <http://world.honda.com/news/2009/c091019GE-Honda-HF120-engine/>, 2010/3/25

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