연료 돌출 시험에 의한 가스터빈엔진의 서지마진 측정

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Fuel Spiking Test for the Surge Margin Measurement in a Gas Turbine Engine

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ABSTRACT

A fuel spiking test was performed to measure the surge margin of the compressor in a gas turbine engine. During the test, fuel spiking signal is superposed on the engine controller demand signals and the combined signals are used to control a fuel control valve. For the superposition, a subsystem composed of a fuel controller and a function generator is used. The real engine test was performed at the Altitude Engine Test Facility (AETF) in Korea Aerospace Research Institute (KARI). In the preliminary test, the fuel spiking signals are in good agreement with the dynamic pressure at the fuel line and at the compressor discharge point. After the preliminary test, a fuel spiking test to measure the surge point at a specific engine speed was performed. The test results show that the fuel spiking test is very effective in the measurement of surge.

초 록

가스터빈엔진 압축기의 서지마진을 구하기 위하여 연료 돌출 시험을 수행하였다. 본 시험에 사용된 연료 돌출 신호는 엔진 제어기 신호에 중첩되어 연료 밸브를 제어하는 데 사용되었으며 신호 중첩을 위해 연료 제어기와 함수 발생기로 구성된 보조시스템이 사용되었다. 한국항공우주연구원의 고공엔진시험설비에서 실제 엔진 시험이 이루어졌으며 예비 시험결과, 연료 돌출 신호는 연료 라인과 압축기 토출부에서의 압력 신호와 잘 일치하였다. 이에 따라 특정 속도에서의 서지점을 측정하기 위한 시험이 수행되었으며 시험 결과 연료 돌출시험이 서지 측정에 매우 효과적임을 확인하였다.

Key Words: Fuel Spiking(연료돌출), Surge Margin(서지마진), Gas Turbine Engine(가스터빈엔진)

1. Introduction

The behavior of a gas turbine engine is usually investigated at the compressor map. In this map, design point and the operating line

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is set up far enough from the surge region for the stable running of the engine. But the operating points at the transient conditions do not follow the operating line exactly.

In the case of steady running condition, the fuel flow rate follows the steady state fuel flow rate and the running line is changed from the steady state working line depending on the acceleration or deceleration rate.

In the case of transient running condition, the engine is over or under fueled compared to the steady state fuel flow rate and the transient running line at acceleration approaches the surge line more rapidly. Usually, maximum acceleration or deceleration rate of an engine is limited by the engine control unit (ECU) to prevent surge or flame out. Therefore, surge initiating method such as fuel spiking is required to measure the actual surge line.

2. Fuel Spiking Test

2.1 Surge Simulation by a Fuel Spiking

A Surge can occur throughout the speed range if the surrounding components force the compressor operating point up in a speed line such that the pressure ratio is increased to the surge line value.

In this case, immediate action process such as opening bleed valves or reducing fuel flow is required to lower the working line and hence recover from surge. If required process is not taken, the compressor flow will re establish itself and then surge again. The surge cycle would continue at a frequency of between five and ten times per second and eventually lead to engine damage. At low engine speeds, locked stall may occur following a surge. If the locked stall occurs, instead of the flow recovering and then surging again, a channel of stall rotates at approximately 50% engine speed in the direction of rotation. It is characterized by the engine running down. In this case, the turbine entry temperature is rapidly increased and the engine must be shut down immediately to avoid the engine damage[1].

Surge margin is defined[1] as equation (1) and affected by the following factors[2].

$$SM = 100 \times (PR_{surge} - PR_{working\ line}) / PR_{working\ line} \quad (1)$$

1) inlet distortion
2) transients of aircraft, throttle, and variable geometry
3) Reynolds number
4) Operating line of engine variation and deterioration.

The surge line of a compressor can be measured in component test, but it is necessary to measure the actual surge lines in an engine, or at least define a surge free region, rather than relying on rig test or predicted data[1].

The purpose of the fuel spiking test is to determine the position of the surge line in the compressor map.

A short term transient shows that the increase of engine speed does not follow the increase of fuel flow rate immediately. A fuel spiking is a sudden increase in the fuel flow followed by an immediate reduction of the fuel flow to its original level[3].

Therefore, a fuel spiking with adequate spiking time and amplitude can raise the pressure ratio in compressor map without change of engine speed. Beside, even though a surge occurred, continuous surge cycle can be avoided. Usually the momentarily injecting fuel is between 100 and 400 % over of its original fuel level around 200 ms[1].

2.2 Test Facility

The real engine test was performed at AETF in KARI. This facility was designed by KARI and Sverdrup Technology, Inc. and constructed at October, 1999.(See Fig. 1)

The test capacity of AETF is listed in Table 1. Aero-propulsion laboratory is in charge of AETF and have developed the test technologies of steady state performance, windmill starting, re lighting, and quick starting in collaboration with Rolls Royce and DERA in UK. Nowadays, this laboratory is developing the test technologies for the transient performance and the unsteady operating.

As a data acquisition system (DAS), a Agilent VXI system composed of A/D converter, data controller, and signal conditioner was used. For the frequency domain analysis, a LMS Pimento system was also used as a FFT analyzer.

The sampling rate of monitoring by the VXI system was 10 samples per second and that of data recording by the FFT analyzer was 20,000 samples per second. For the dynamic pressure measurement, Kulite ETM 375 1000A type sensors were used at fuel line and ETM 375 100A type was used at the compressor discharge location.

2.3 Test Engine

For the fuel spiking test, the standard engine of aero-propulsion laboratory in KARI was used. This engine is a turbojet engine and consists of 3 rows of axial compressor and single row of turbine. The fuel supply of the engine is controlled by a fuel control valve managed by the ECU.

The ECU determines the fuel flow rate from the information such like engine speed, exhaust gas temperature, and so on. It is programmed to limit acceleration rate for the surge protection. In this test, a subsystem composed of a fuel controller and a function generator was used to manipulate the fuel flow rate without any modification of the engine controller.

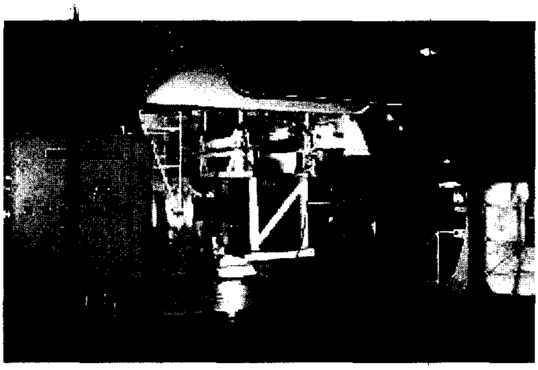

Fig. 1 AETF test cell in KARI

Table 1. Test capacity of AETF

Item		Value
Test capacity	Max. thrust Max. altitude Max. speed	3,000 lbf 30,000 ft Mach 1
Number of measuring channel		600
Reliability	Net thrust SFC	0.54 % @SLS 0.59 % @SLS

2.4 Fuel Controller

A fuel controller was used to modify the fuel control demands from the engine controller. The schematic overview of the fuel control system is shown in Fig. 2.

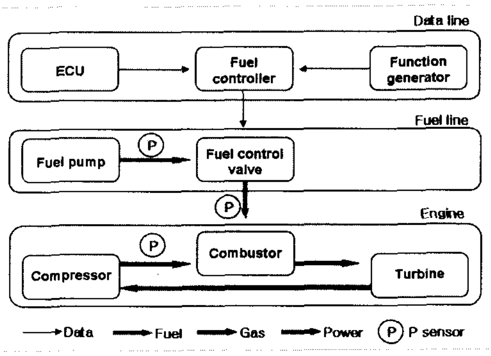

Fig. 2 Schematic overview

The opening position of the fuel control valve in the engine is controlled by current signal. The fuel controller sends the combined fuel spiking current signal to the fuel control valve. The fuel spiking signals could be selected by a function generator connected to the fuel controller.

An exterior view of the fuel controller is shown at Fig. 3, Fig. 4 and 5 show the block diagram and the circuit of the fuel controller.

The inputs of the fuel controller are the ECU demand signal in current, the fuel spiking signal from the function generator, and the trigger signal to the function generator from DAS. The fuel controller circuit converts the ECU demand signal to a voltage signal for the adding process with the fuel spiking signal. After the process, the combined signal is inverted to a current signal again and sent to the fuel control valve.

The outputs are the ECU demand converted to a voltage signal and the combined voltage signal. Both signals are sent to the DAS to monitor the consistency of these signals. During the fuel spiking test, the engine controller responses against the transient behavior of the engine was also monitored.

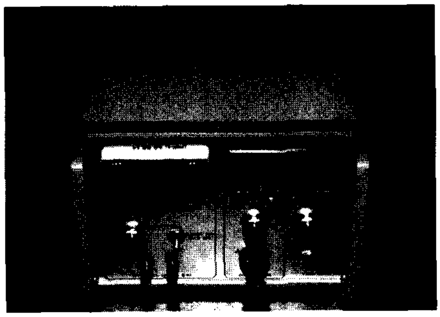

Fig. 3 Exterior view of the fuel controller

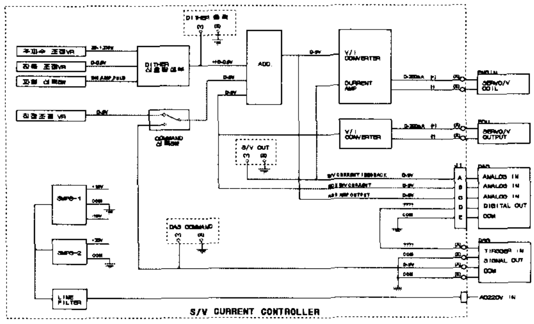

Fig. 4 Block diagram of the fuel controller

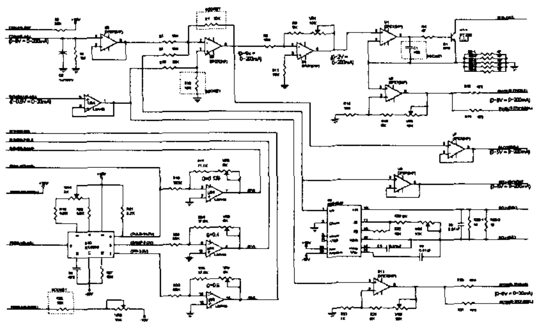

Fig. 5 Circuit of the fuel controller

3. Results and Discussion

The standard test condition of Mach 0.7 at sea level and standard atmosphere was set up as fuel spiking test condition. The spiking duration was selected as 25 ms (20 Hz in function generator) and 50 ms (10 Hz) by experiments. Below the frequency of 10 Hz, the test data showed considerable change of the engine speed and the engine controller attempted to change the fuel flow rate accordingly. Therefore this frequency was considered as the minimum fuel spiking test frequency for the test engine.

In the idle state of the engine at standard test condition, fuel control valve opening signal by the engine control unit was considered as a base reference level of the fuel spiking test. The fuel spiking signals used in the preliminary test are in Table 2.

Table 2. Preliminary test data

Time(ms)	Spiking signal ratio (%)*							
25	17	21	25	29	34	38	42	46
50	17	21	45	29	-	-	-	-

* Current signal ratio of the spiking to the base level

Each fuel spiking signal was tested in pair by 10 s interval and the interval between the pairs was about 20 s.

The signals of the fuel controller demand and those of the fuel control valve rear point pressure are compared in Fig. 6 The pressure signals of the fuel control valve rear point reflect the mechanical operations of the fuel control valve. The time delay between the demand of the fuel controller and the response of the fuel control valve was less than 10 ms.

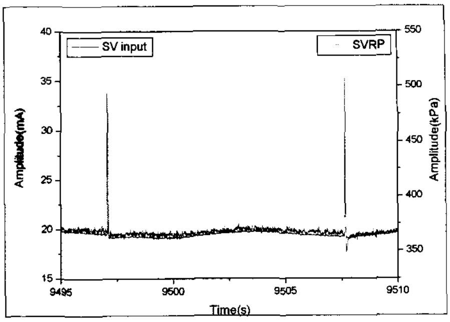

Fig. 6 Comparison of the spiking signals

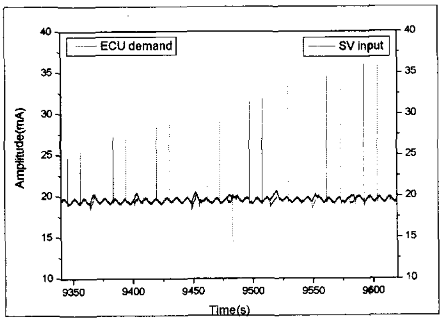

Fig. 7 Fuel controller spiking signals (20 Hz)

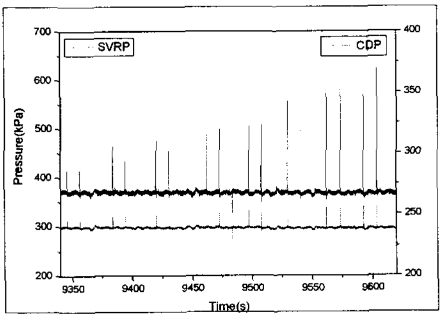

Fig. 8 Spiking pressure signals (20 Hz)

The local fluctuation of the demand signals are in good agrement with that of fuel pressure signals. The small disturbances throughout the pressure signals of the fuel control valve rear location are the reflection of the valve actuating signals. These signals could not be clearly identified because of the aliasing in DAS. The sampling rate of DAS was smaller than the actuating frequency. But the actuating frequency is not important in that the fuel control valve operates well.

Figure 7 and 8 shows the test results at 25 ms spiking time period. The engine controller demand agrees well with the fuel controller output excluding the spiking signals. The pressure signals at the fuel control valve rear location and compressor discharge location also show that the fuel spiking was effective through the entire engine components. Fig. 9 and 10 shows the results at 50 ms spiking time period.

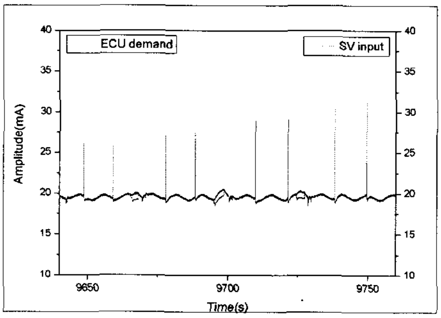

Fig. 9 Fuel controller spiking signals (10 Hz)

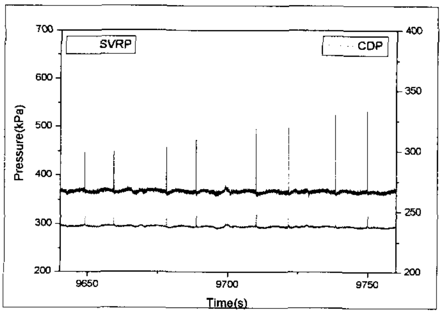

Fig. 10 Spiking pressure signals (10 Hz)

Figure 11 shows the change of the operating point on the compressor map by the fuel spiking test. This compressor map is derived from the data of engine performance test. In the figure, the base point and 4 fuel spiking test points at 25 ms in the preliminary test are represented by circle marks. These points correspond to 21 %, 29 %, 38 %, and 46 % spiking signal ratio.

In the compressor map, the pressure ratio should be a total pressure ratio but the pressure ratio in the figure is derived from the static compressor discharge pressure value. That is because the product engines measure the static pressures at the compressor discharge location. The air flow rate in the figure was normalized by the design point value and the other corrected parameters are as follows.

$$\delta = P_{inlet} / 101.325 \quad (2)$$

$$\theta = T_{inlet} / 288.15$$

$$W_{A\theta} = W_A \sqrt{\theta} / \delta$$

$$N_C = N / \sqrt{\theta}$$

After the confirmation of the fuel spiking operation in the preliminary test, surge measurement test was carried out at different speed. The data of surge measurement test are also in the Fig. 11

In this test, surge was detected by loud bang when the fuel spiking signal was triggered above certain amplitude.

The fuel spiking effect was also detected by the vibration of engine. In Fig. 12, two vibration peaks from the fuel spiking signals are noticed at the rotor speed frequency. Because the pressure ratio jump in the compressor acts like an impulse to the engine, vibration peaks are observed in wide range of frequency axis.

The surge margin was defined in terms of the inlet mass flow on the working line and on the surge line for a single speed[4]. The surge measurement test in Fig. 11 showed a surge margin of about 17 percent.

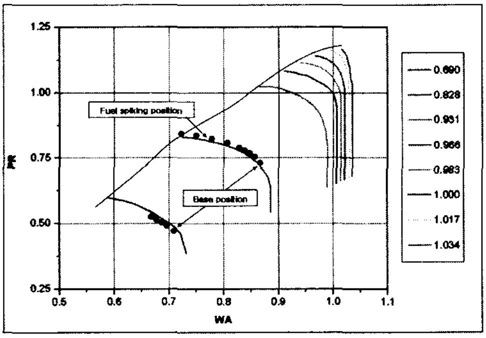

Fig. 11 Test points in the compressor map

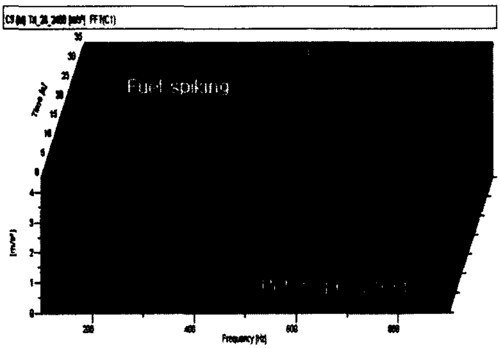

Fig. 12 Engine vibration data (x direction)

4. Conclusion

The test method of fuel spiking was studied and the real engine test was performed at altitude engine test facility in KARI. For the test, a subsystem consists of a fuel controller and a function generator was used. The fuel controller successfully superposed the fuel spiking signal onto the demand signals of the engine control unit without any transformation of the demand signals. The fuel spiking effects are detected by vibration sensors as well as dynamic pressure sensors. The dynamic pressure data show pressure peaks at the fuel line and compressor discharge location. And the vibration data show impulse characteristic of the engine. The test result was analyzed on the compressor map from the engine performance test. In the compressor map, the operating point moved up to the surge line along the speed line by the fuel spiking test. The test result shows that the fuel spiking test is very effective in the measurement of surge and a surge margin at a single speed was calculated. More fuel spiking tests are scheduled at different engine speeds to find out surge points at each speed. These experimental data will give the actual surge line information of the real engine.

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