A Fuel Spiking Test for the Surge Margin Measurement in Gas Turbine Engines

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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 was superimposed on the engine controller demand and the mixed signals were used to control a fuel line servo-valve. For the superimposition, a subsystem composed of a fuel controller and a function generator was used. During the fuel spiking test, the original scheduled fuel signals and the modified signals were compared to guarantee the consistency excluding the spiking signals. The spiking signals were carefully selected to maintain the engine speed constant. The fuel spiking effects were checked by three dynamic pressure sensors. Sensors were placed before the servo-valve, after the servo-valve, and after the compressor location, respectively. The modulations of the spiking signal duration and fuel flow rate were examined to make the operating point approach the surge region. The real engine test was performed at the Altitude Engine Test Facility (AETF) in Korea Aerospace Research Institute (KARI). In the real engine test, fuel spiking signals with 25~50 ms of spiking signal time and 17~46 % of base fuel flow rate condition were used. The dithering signal was 5 ~6 mA at 490 Hz. The test results showed good agreement between the fuel spiking signals and the fuel line pressure signals. Also, the compressor discharge pressure signals showed fuel spiking effects and the changes of the operating point on the compressor characteristic map could be traced.

Introduction

Transient Behavior of a Gas Turbine Engine

The behavior of a gas turbine engine is usually investigated at the compressor map. In this map, design point and the operating line 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 steady running conditions, the fuel flow follows the steady state fuel flow and the running line is changed from the steady state working line depending on the acceleration or deceleration rate. Figure 1 shows the steady running lines at steady accelerations.

In transient running conditions, the engine is over or under fueled compared to the steady state fuel flow as shown in Figure 2 and the transient running line at acceleration approaches the surge line more rapidly as shown in Figure 3. Usually, maximum acceleration or deceleration rate of an engine is limited by engine controller to prevent surge or flame out. Therefore, surge initiating method such as fuel spiking is required to measure the actual surge line.

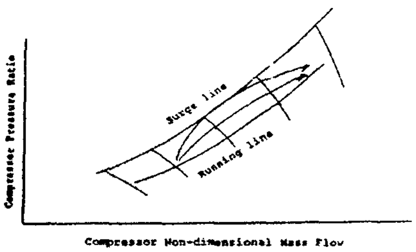

Fig. 1 Steady running (acceleration)

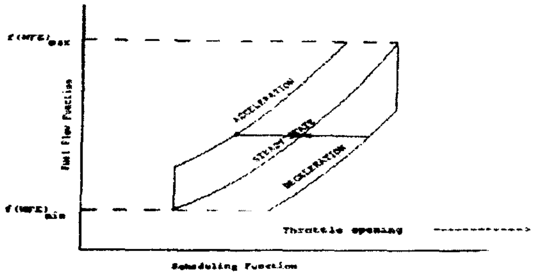

Fig. 2 Fuel scheduling function

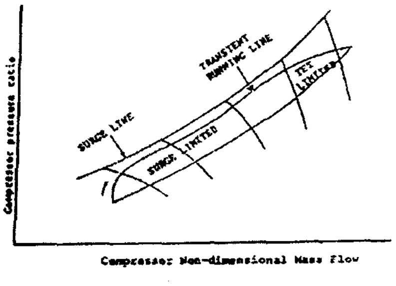

Fig. 3 Transient running (acceleration)

Test Method

A Surge Simulation by a Fuel Spike

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)]

The surge margin is defined[1)] as equation (1) and affected by followings.[2)]

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

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

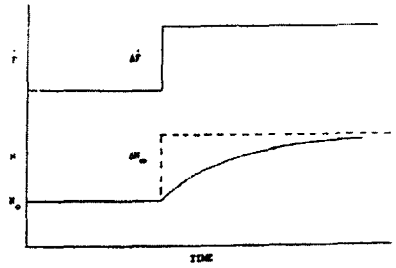

Fig. 4 Short-term transient

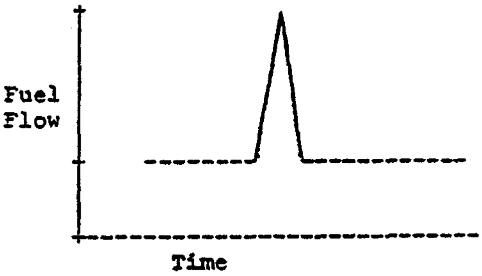

Fig. 5 Fuel spike shape

A short term transient shows that the increase of engine speed doesn't follow the increase of fuel flow immediately. (See Figure 4) A fuel spike is a sudden increase in the fuel flow followed by an immediate reduction of the fuel flow to its original level[3)] as shown in Figure 5.

Therefore, a fuel spike with adequate time period 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)]

Test Equipments

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 Figure 6) 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.

For the DAS, HP VXI E1401B mainframe was used. The sampling rate of monitoring system was 10 samples per second and that of data recording system was 100 samples per second.

For the dynamic measurement of pressures, ETM-375-1000A type kulite sensors were used at fuel line and ETM-375-100A type at the compressor discharge point.

Table. 1 Test capacity of AETF

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

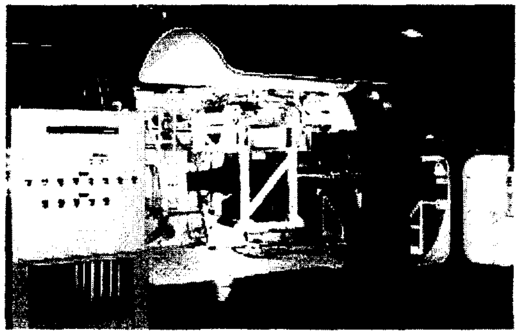

Fig. 6 AETF test cell in KARI

Test Engine

For the fuel spike 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 servo-valve controlled by the engine control unit (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.

Fuel Controller

A fuel controller was used to modify the fuel control demands from the engine controller. The schematic view of the fuel control system is shown in Figure 7.

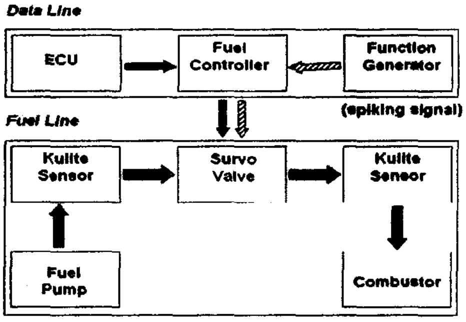

Fig. 7 Overview of fuel control

The opening position of the servo-valve in the engine is controlled by 0-200 mA range current signal and the servo-valve is activated by a dithering signal with 5-6 mA current at 490 Hz. The fuel controller sends the dithering signal as well as the combined fuel spike signal to the servo-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 Figure 8. Figure 9 and 10 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 (data acquisition system). 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 servo-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.

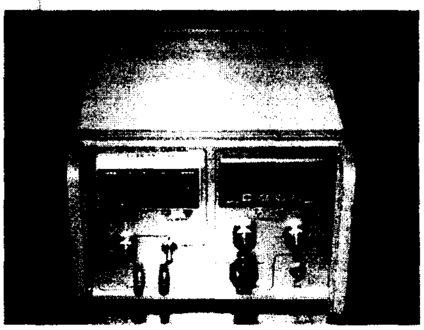

Fig. 8 Exterior view of the fuel controller

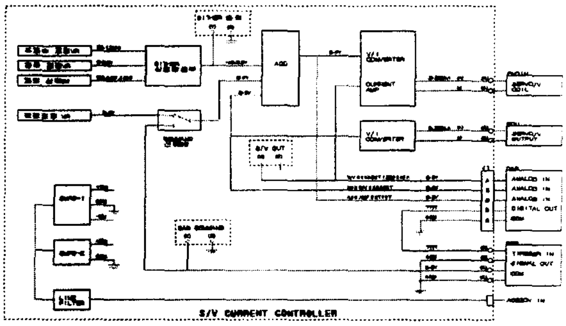

Fig. 9 Block diagram of fuel controller

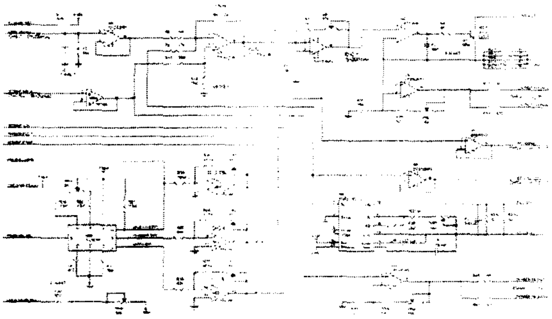

Fig. 10 Circuit of fuel controller

Results and Discussion

Fuel Spiking Test

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 unexpected changes of the engine speed and the engine controller attempted to change the fuel flow. Therefore this frequency was fixed as the minimum fuel spike frequency for the test engine.

In the engine idle state at standard test condition, servo-valve opening signal by the engine controller was 19.5 mA. This was considered as a base fuel flow level of the fuel spiking test. The fuel spiking signals used in the test are in Table 2.

Table. 2 Fuel spiking test signals

Time (ms)	Servo-valve current (mA)							
25	3.2	4.0	4.8	5.6	6.4	7.2	8.0	8.8
50	3.2	4.0	4.8	5.6	-	-	-	-
	Spike signal ratio (%)*							
	17	21	25	29	34	38	42	46

* Spike current to the base current (19.5 mA) ratio

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

The signals of the fuel controller demand and those of the servo-valve rear point pressure are compared in Figure 11. The pressure signals of the servo-valve rear point reflect the mechanical operations of the servo-valve. The time delay between the demand of the fuel controller and the response of the servo-valve was less than 10 ms. The local fluctuation of the demand signals agreed well with that of actual fuel flow signals. The small disturbances throughout the pressure signals of the servo-valve rear location are reflection of the dithering signals. These signals could not be clearly identified because of the aliasing in DAS. The sampling rate of DAS was smaller than the dithering frequency of 490 Hz. Yet the dithering frequency was not significant because the servo-valve operated well as expected.

Figure 12 and 13 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 servo-valve rear location and compressor discharge location also show that the fuel spikes were effective through the entire engine components. Figure 14 and 15 shows the results at 50 ms spiking time period.

Figure 16 shows the changes of the operating point on the compressor map. This compressor map is derived from the data of engine deck. In the figure, the base point and 4 fuel spiking test points at 25 ms are represented by circle marks. The first point corresponds to the 21 % over fueled spiking and the last one to the 46 %.

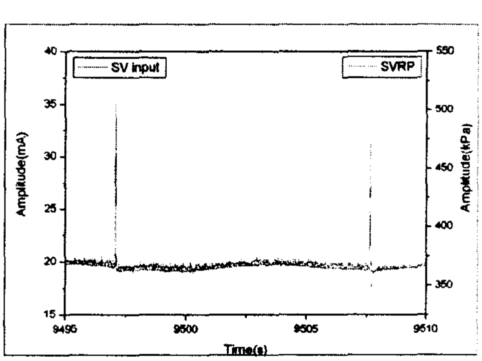

Fig. 11 Comparison of the spiking signals

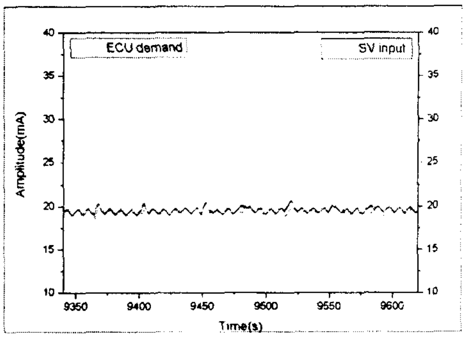

Fig. 12 Fuel controller spiking signals (20 Hz)

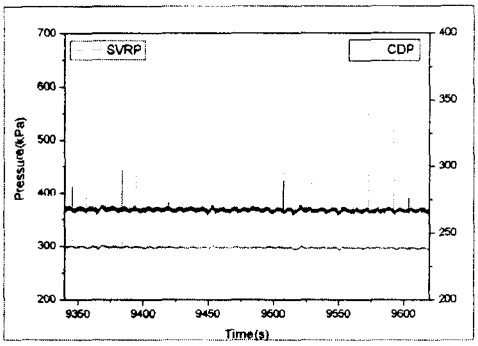

Fig. 13 Spiking pressure signals (20 Hz)

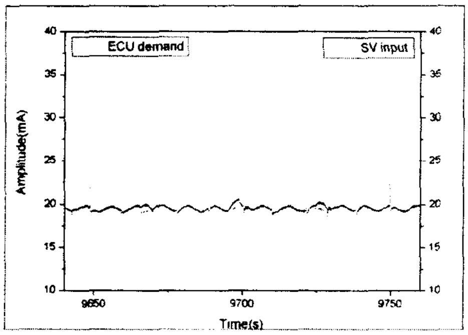

Fig. 14 Fuel controller spiking signals (10 Hz)

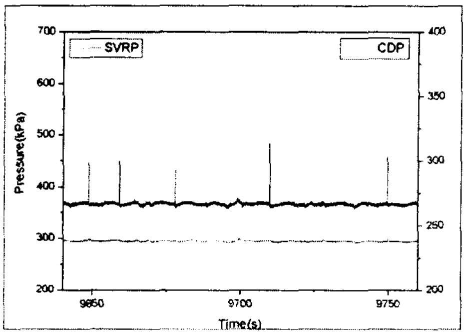

Fig. 15 Spiking pressure signals (10 Hz)

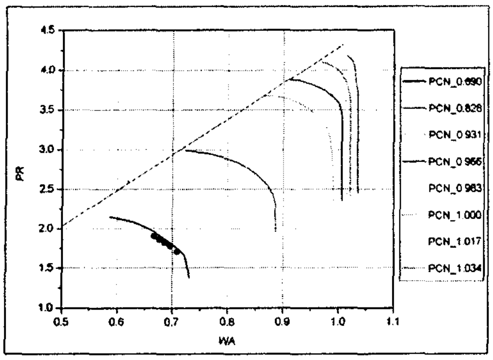

Fig. 16 Operating point shifts by fuel spikes

The pressure ratio at the compressor map should be the total pressure ratio but the pressure ratio in the figure used static compressor discharge pressure values. 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.

$$\begin{aligned} \delta &= P_{inlet} / 101.325 \\ \theta &= T_{inlet} / 288.15 \\ W_{A\theta} &= W_A \sqrt{\theta} / \delta \\ N_C &= N / \sqrt{\theta} \end{aligned} \quad (2)$$

The test results show that the surge line is located still beyond the maximum fuel spiking test point. But they assured the possibility of the surge margin measurement. On next test, the actual measurement of the surge margin is scheduled. By then, the sampling rate of DAS will be improved until 10 kHz and more data channels at high sampling rate will be provided.

Conclusion

A test method of fuel spiking was studied and actual engine tests were performed at AETF in KARI by aero-propulsion laboratory. In the test, a subsystem consists of a fuel controller and a function generator was used. The fuel controller could successfully superimpose the fuel spike signals onto the engine controller demand signals. The dynamic pressure sensors located at the servo-valve front, rear, and compressor discharge point showed the fuel spiking effects at the fuel flow and compressor. The test result was analyzed on the compressor map and it showed the fuel spiking effects by the shifts of operating point toward the surge region. On next test, the actual surge margin of the engine will be measured with more improved DAS.

References

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