Uncertainty Analysis and Improvement of an Altitude Test Facility for Small Jet Engines

Yongmin Jun, Inyoung Yang*, Chun Taek Kim**, Soo Seok Yang*** and Dae Sung Lee******
Aeropropulsion Department
Korea Aerospace Research Institute, Daejeon, Korea 305-333

Abstract

The verification and improvement of the measurement uncertainty have been performed in the altitude test facility for small gas turbine engines, which was built at the Korea Aerospace Research Institute (KARI) in October 1999. This test is performed with a single spool turbojet engine at several flight conditions. This paper discusses the evaluation and validation process for the measurement uncertainty improvements used in the altitude test facility. The evaluation process, defined as tests before the facility modification, shows that the major contributors to the measurement uncertainty are the flow meter discharge coefficient, the inlet static and total pressures, the cell pressure and the fuel flow rate. The measurement uncertainty is focused on the primary parameters of the engine performance such as airflow rate, thrust and specific fuel consumption (SFC). The validation process, defined as tests after the facility modification, shows that the measurement uncertainty, in seal level condition, is improved to the acceptable level through the facility modification. In altitude test conditions, the measurement uncertainties are not improved as much as the uncertainty in sea level condition.

Key Word : Altitude Engine Test, Turbojet Engine, Measurement Uncertainty

Introduction

Today, the altitude ground test has become the primary method to determine the performance of aircraft engines. As the requirements for engine performance become more and more severe, the measurement uncertainty methodology has been advanced significantly in the past several years. To meet the required level of the measurement accuracy of the engine performance during the altitude ground test, an altitude test facility has to be proven through an uncertainty validation process, which can quantify the contributions of individual measurement parameters to the uncertainty of airflow rate, thrust and specific fuel consumption.

In the early 1970's, Abernethy and Thompson introduced an engineers' measurement uncertainty methodology to the engine industries. Smith and Wehofer used uncertainty analysis for the engine performance test and discussed how to utilize the uncertainty results in deriving and identifying the factors that must be controlled.

The altitude test facility, named Altitude Engine Test Facility (AETF) has been designed and constructed at KARI by Sverdrup Technology Inc. in 1999. To enhance the measurement accuracy and the reliability of AETF, a program for the measurement uncertainty improvement is in progress.

* Researcher
** Senior Researcher
E-mail : ymjun@kari.re.kr, TEL : 042-860-2031, FAX : 042-860-2626
*** Principal Researcher, Head of Aeropropulsion Department
**** Principal Researcher, Director of Aeronautics Program Office

The uncertainty analysis of AETF, which was done by Yoon, suggested some methods for the facility modification. In this paper, the proposed methods for the uncertainty improvement will be confirmed through the evaluation and the validation test. The techniques used in this uncertainty analysis are consistent with those presented in the AIAA and ASME documents.

Description of the Facility

AETF is a direct connecting type altitude test facility designed for the small gas turbine engines of 3,000 lbf-class or less. The specifications of the facility are presented in Table 1. AETF is equipped with test cell, air supply/exhaust system, fuel system, facility control system, and data acquisition system as shown in Fig. 1. Thrust stand is located at the upper part of the test cell. It contains four load cells. Two load cells are used for thrust measurement and the other two are equipped for tare load measurement. The test engine is connected directly to the bellmouth and a subsonic venturi meter is installed at the upstream of stilling chamber for the airflow measurement. Two single-stage centrifugal compressors, which can be controlled by the inlet guide vanes for the air discharge condition, are used for supplying and exhausting the air in series or parallel mode. Fuel system can control the fuel temperature within the range of 40~75℃. Fuel flow rate is measured by a coriolis flow meter with high accuracy (±0.1 reading). Facility control system consists of 7 PLC racks, a Windows NT workstation and GE Cimplicity® software. Data acquisition system has about 794 channels and its details are listed in Table 2.

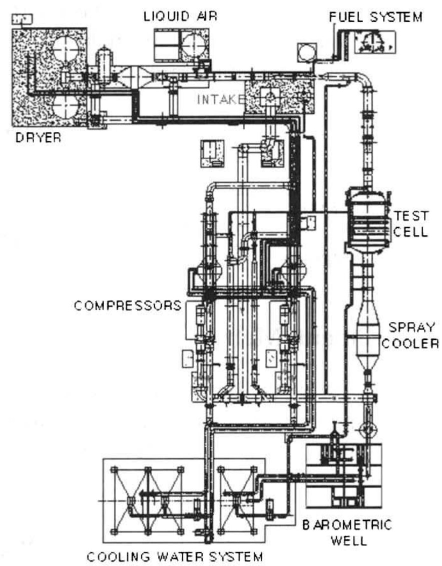

Fig. 1. AETF Layout

Table 1. AETF Specifications

Altitude	0~30,000 ft
Mach Number	0~1.0
Inlet Temperature	-75~110 ℃
Inlet Pressure	31~350 kPa
Max. Flow rate	23.4 kg/s @192kPa, 286K
Max. Thrust	3,000 lb

Table 2. DAS Channels

Channel	Number
Thermocouple	256
Pressure	260
Analog signal	120
Relay input/output	128
Tachometer	8
Dynamic pressure	10
Vibration	12

Test Conditions and Configurations

Table 3 shows that the test conditions of the measurement development program. After the facility modification, tests were performed at the same conditions. To verify the measurement uncertainty under the engine part-load conditions, engine tests were conducted at several percentage RPM (PCN) of 77.2, 83.3, 89.4, and 95.5%. The simulated flight condition is Mach number 0.7, at sea level condition. To supply the air, two kinds of the air supply system modes were used. The direct-supply (blowing) mode was used to simulate sea level condition and the direct-exhaust (suction) mode was used to simulate the altitude conditions. In the direct-supply mode, the air supply system pressurizes the inlet pressure and the cell pressure is controlled to maintain the ambient pressure. In the direct-exhaust mode, the air supply system sucks the test cell air to depressurize it. To verify the improvement of the measurement uncertainty, the tests were performed before and after the facility modification.

Table 3. Test Conditions

	Flight Conditions		
MN	0.5	0.7	0.85
Altitude	Sea Level(SL)	SL	SL
			20,000ft

Measurement Method

The selected performance parameters for the measurement uncertainty analysis are airflow rate, gross/net thrust and SFC. The airflow was measured with the subsonic venturi flow meter (Badger Meter Inc., Model BVF-IF 19.370×11.000) and was calculated by the following equation.

$$W_A = \frac{\pi d^2}{4} C_d Y \sqrt{\frac{2\rho\Delta P}{1-\beta^2}} \tag{1}$$

where, W_A is the mass flow rate, d the throat area of the venturi, C_d the discharge coefficient, Y the expansion coefficient, ρ the density of the air, ΔP the pressure difference in the venturi, and β the throat diameter ratio. The inlet flow total temperature and total pressure were measured at the flow meter upstream with temperature probes (RTD) and pressure probes (MKS690A/698A), respectively.

The thrust was measured with two load cells at the thrust stand and the tare load was recorded just before each test. The control surface used in AETF to determine the thrust is shown in Fig. 2.

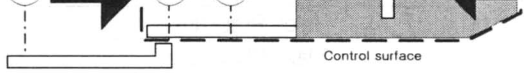

Fig. 2. Engine Thrust Control Surface

The gross thrust was the sum of pressure-area terms and momentum around the control surface. Static pressure and total pressure were measured at 01 & 05 section with pressure rakes and total temperature was measured with temperature rake at 05 section. The gross thrust of an engine was measured from the following equation.

$$F_G = F_{LC} + F_{TARE} + W_{A,01}V_{01} + (P_{S,01} - P_{S,90}) \times (A_{0,o} - A_{0,i}) + (P_{S,02} - P_{S,90})A_{0,i} \tag{2}$$

where F_G is the gross thrust, F_{LC} the force measured by load cells(Interface, Model 1100), F_{TARE} the tare load, $W_{A,01}$ the air flow rate measured by the venturi flow meter, V_{01} the velocity at the inlet, $P_{S,01}$ the static pressure acting on the inlet seal cross section area, $(A_{0,i}-A_{0,o})$ the inlet seal cross section area, $P_{S,02}$ the pressure of the engine inlet, $A_{0,i}$ the inlet flow area, and $P_{S,90}$ the test cell static pressure.

The net thrust was, by definition, the gross thrust minus the ram drag as the following equation.

$$F_N = F_G - W_{A,01}V_\infty \tag{3}$$

where V_∞ is the simulated flight speed.

The specific fuel consumption(SFC) is defined as Eq.4.

$$SFC = Wf/FN \tag{4}$$

The fuel flow was measured with a calibrated coriolis flow meter (Micro motion), which had ±0.1% reading accuracy.

Uncertainty Methodology

Consider the uncertainty of a result r of a data reduction equation with variables Xi, which takes the form of Eq (5) as followed.

$$r = r(X1, X2, X3, \cdots, Xi) \tag{5}$$

$$Ur = \sqrt{B_r^2 + P_r^2} \tag{6}$$

$$Br = \sqrt{\sum_i (\theta_i B_i)^2} \tag{7}$$

$$Pr = \sqrt{\sum_j (\theta_j P_j)^2} \tag{8}$$

$$Pi = kSi \tag{9}$$

Ur is the expanded uncertainty, Bi the systematic uncertainty, Pi the random uncertainty, the sensitivity coefficient, which is defined as $\partial r/\partial Xi$, and k is the coverage factor (k=2 in this paper). The Uncertainty Percentage Contribution (UPC) is defined as Eq.10.

The UPC values show the percentage contributions of the individual measurement variables to the measurement uncertainty. Comparing the UPC values identifies the measurement variable that makes the largest contribution to the uncertainty. According to this UPC analysis, the facility modification items and methods were set up.

$$UPC_i = \frac{(\partial r/\partial X_i)^2 U_i^2}{U_r^2} \times 100 \tag{10}$$

Facility Modification Details

Fig.3 shows 6 changed items by the AETF modification program. Temperature measurement method of an airflow meter changed from 2 point temperature probes to 2×11 points temperature rakes with RTD. Inlet pressure and cell pressure were measured with FCS(facility control system) pressure transmitters which have relatively lower accuracy(±0.075%FS) and DAS(data aquisition system) received the same data. DAS pressure transmitters with much higher accuracy(±0.01%FS) installed, and FCS and DAS have separate pressure channels for inlet pressure and cell pressure. Because AETF originally designed for 3,000lbf class engines, the fuel flow meter was selected for that class of engine. Required full range of fuel flow meter for 1,000lbf class engine should be 1/3 of the original fuel flow meter. Fuel flow meter changed from MicroMotion 050 coriolis flow meter to MicroMotion 025 coriolis flow meter and the full range reduced by half. In order to supply more uniform flow into engine, a new duct configuration was adopted for better sealing and less disturbance. Cell pressure control logic was modified to have less sensitivity and faster convergence.

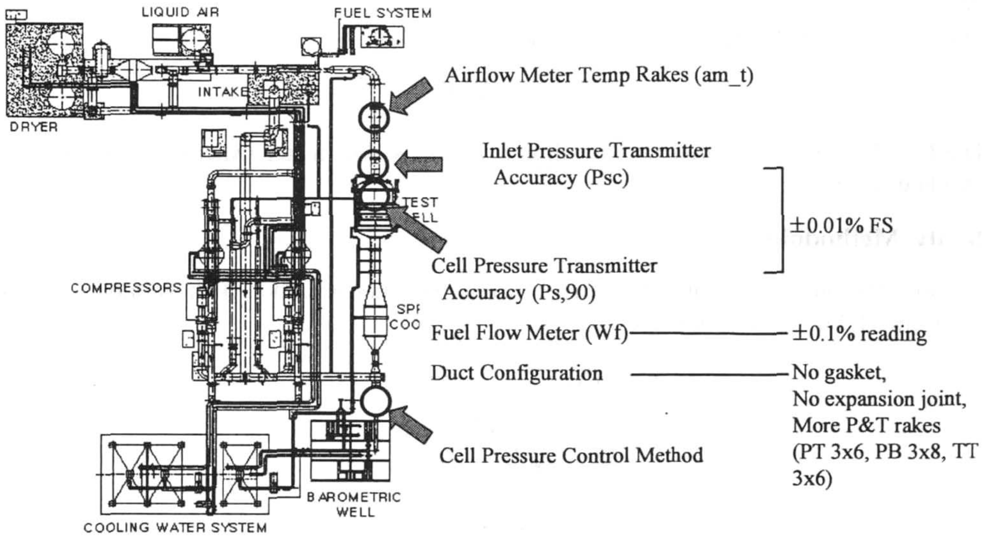

Fig. 3. Facility Modification Details

Result

Various Flight Conditions

The systematic uncertainty (Bi) included the uncertainties of the measuring sensors, the environments (temperature and pressure), geometric characteristics, and data acquisition system (DAS) characteristics. The random uncertainties (Pi) were analyzed with 10 seconds recorded data at 10Hz and the confidence level was 95%. The results will be shown in two parts, one is part-load test result and the other is the various flight conditions test result.

Airflow measurement uncertainty was evaluated under the various flight conditions and their UPC values were observed. It is clear that the UPC values were influenced by the various flight conditions and the major uncertainty contributors are Cd_in, am_t, am_dp, am_p. Cd_in is the airflow meter discharge coefficient, am_t the airflow meter temperature, am_dp the pressure difference through the airflow meter and am_p the pressure of the flow meter. The airflow was calculated as shown in Eq.11.

Airflow = WA (Cd_in, am_t, am_p, am_dp, gi(flow meter geometrical characteristics)) (11)

But gi (flow meter geometrical characteristics) were ignored in uncertainty analysis because of their small contributions. Fig.4 shows that the major contributors to the airflow uncertainty are Cd_in and am_t. Sonic flow meter would be a good answer to improve the accuracy of Cd_in but it costs too much considered the improvement. The facility modification improved the measurement uncertainties by reducing temperature uncertainty and the worst airflow uncertainty was improved from 0.78%(@MN0.85 20kft) to 0.73%(@MN0.5 SL) as shown in Fig. 4. This maybe the best result of uncertainty improvement of airflow unless Cd_in uncertainty is reduced.

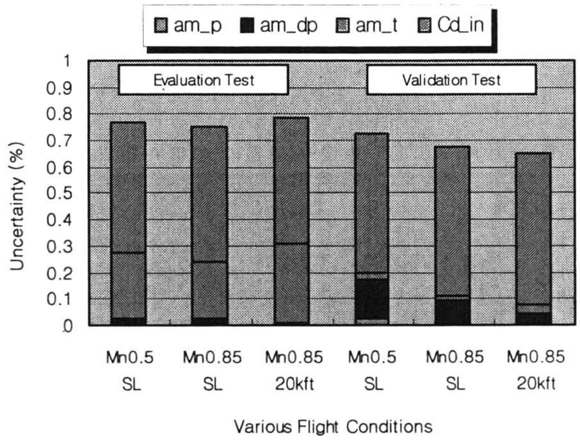

Fig. 4. Airflow Uncertainty Improvement under Various Flight Conditions

Gross Thrust measurement uncertainty was defined as follows.

Gross Thrust = FG (Cd_in, am_t, am_p, am_dp, gi (flow meter geometrical characteristics), inlet air pressure & temperature, inlet duct configuration, scaled force) (12)

The minor contributors were ignored in this uncertainty analysis. Gross Thrust measurement uncertainty and its UPC values are shown in Fig. 5. P,05 and PS,05 are the total and static pressure measured at 05 section to quantify input force and fm is the scaled force measured by load cells. PS,90 is cell pressure. At the evaluation test, PS,90 was the biggest uncertainty contributor irrelevant to the Mn and altitude. The main uncertainty contribution was cell pressure fluctuation and, in a case, the random uncertainty of cell pressure was about 30 times bigger than the systematic uncertainty. It means that cell pressure fluctuated severely and the facility control couldn't reduce it properly. A new method for cell pressure control was adopted in the validation test and it produced better results in the SL test conditions as shown in Fig.5. The worst measurement uncertainty of gross thrust was improved from 1.39%(@MN0.5 SL) to 0.49%(@MN0.85 20kft). Under the altitude condition at validation test, the uncertainty was not improved much because the random uncertainty of cell pressure increased. To remove this kind of cell pressure instability, further study for cell pressure control is in progress.

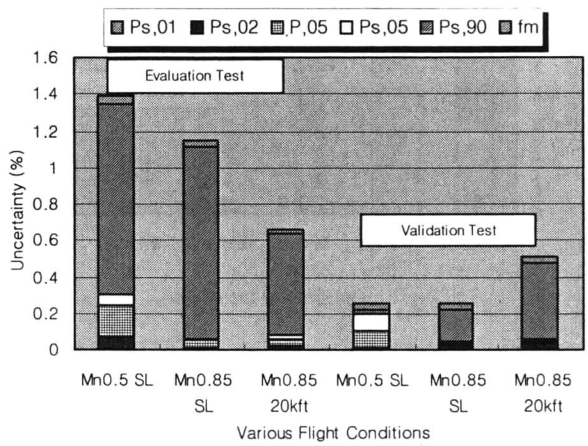

Fig. 5. Gross Thrust Uncertainty Improvement under Various Flight Conditions

Net Thrust was defined as Eq.3 and its measurement uncertainty included more uncertainty factors than gross thrust as Eq.12

$$\text{Net thrust} = \text{FN}\ (\text{Ur}\ (\text{FG}),\ \text{Ur}\ (\text{V})) \tag{13}$$

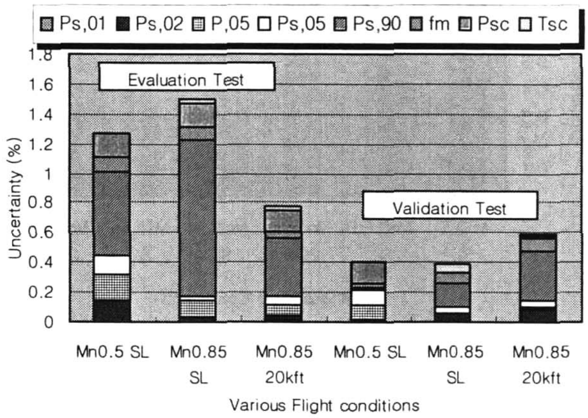

Fig. 6. Net Thrust Uncertainty Improvement under Various Flight Conditions

where Ur (V) = fn (PSC, TSC). The subscript "SC" means the section where the simulated flight speed (V) was decided. The net thrust measurement uncertainty is shown in Fig.6 and the major contributors were PS,90, PS,02, P,05 and PSC. Analyzing the uncertainties of PS,90 and PSC revealed that systematic uncertainty was dominated by sensor accuracy and random uncertainty was dominated by cell pressure fluctuation. By adopting the modified facility control logic and higher accuracy sensors, the worst net thrust uncertainty was improved from 1.55%(@MN0.85 SL) to 0.58%(@MN0.85 20kft).

SFC is defined as Eq.4 and Fig. 7 shows that fuel flow rate was another major uncertainty contributor. By replacing the fuel flow meter and reducing uncertainty of PS.90, the measurement uncertainty SFC was improved from 1.78%(@MN0.85 SL) to 0.61%(@MN0.85 20kft) and PS,90 was still the major uncertainty contributor in altitude case.

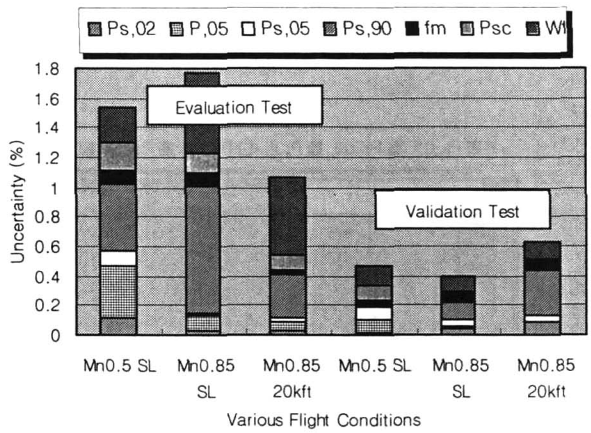

Fig. 7. SFC Uncertainty Improvement under Various Flight Conditions

Engine Part Load

Airflow UPC analysis from the uncertainty evaluation test is shown in Fig.8. In this figure, the major contributors to the airflow uncertainty is Cd_in and am_t. To reduce am_t uncertainty, the airflow meter temperature probe was replaced by two temperature rakes, which have 11 measuring points. In order to supply more uniform flow into the engine, the inlet duct configuration was changed and the duct configuration contribution to the airflow uncertainty was quantified to about 2 ~ 4%. The validation test result of the airflow uncertainty after the facility modification is shown in Fig.9 and the uncertainty has been improved up to 16% when the new duct and new temperature rakes are used.

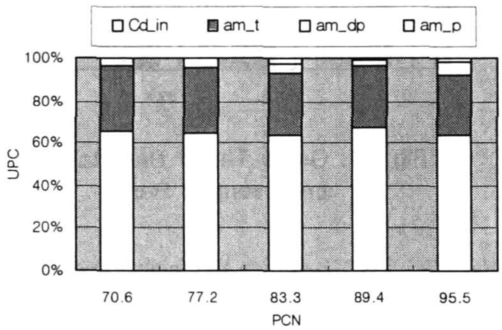

Fig. 8. Evaluation Test Result of Airflow UPC

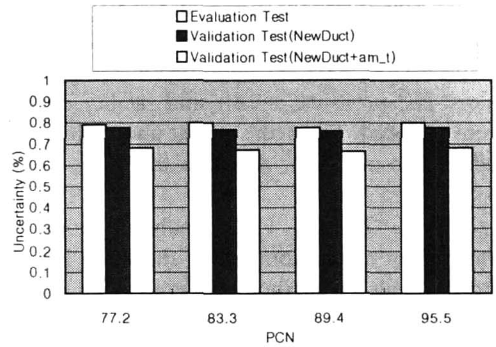

Fig. 9. Airflow Uncertainty Improvement Result

Gross Thrust UPC analysis from the uncertainty evaluation test is shown in Fig. 10. In this figure, major contributors such as P,05 and Ps,90 are obviously presented and among them, PS,90(cell pressure) random uncertainty appeared dominant to the UPC, after PNC=89.4 case. Random uncertainty of cell pressure is originated from the air supply/exhaust system control, including control valves and control logic, and cell pressure instability. Mach No. is simulated by the pressure ratio of the inlet and the cell pressure, and the cell pressure fluctuation is proportional to the ratio. Especially a control valve located right after the test cell is the major factor to the cell instability(fluctuation) because small valve motion makes bigger pressure fluctuation under higher pressure. Because of this, the cell instability increased rapidly above a certain Mach No. (a pressure ratio) but the facility control system was not sensitive enough to reduce the fluctuation. To decrease this high random uncertainty, a new control method was adopted. The required controllability of the system should be enable to keep the cell fluctuation less than 20Pa when the supply pressure and the cell pressure are 140kPa and 101kPa respectively. Active PI(proportion & integration) control method was employed for the previous control logic and the frequency of the cell pressure oscillation was order of 10 Hz. Regarding to the size of the facility, active control may not be able to eliminate this perturbation with this size of frequency and amplitude. For the new control method, a combination of active control and manual control was employed and the active control logic changed to be less sensitive and the PI coefficients were tuned with trial and error method before the validation test.

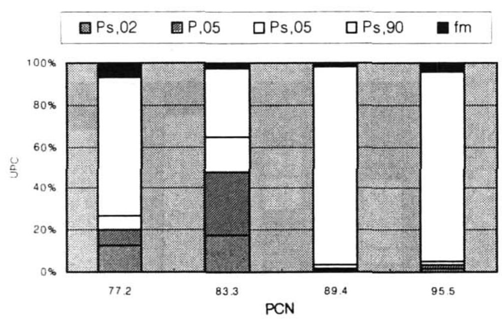

Fig. 10. Evaluation Test Result of Gross Thrust

By using a higher accuracy cell pressure sensor (Mensor 4000, ±0.01%FS), the systematic uncertainty of PS,90 was reduced too. Fig.11 shows the facility modification result of the gross thrust. The evaluation test result is shown in the first case where the cell pressure fluctuation and the old duct configuration are included. In the second case, the high accuracy cell pressure sensor and the airflow meter temperature rakes were excluded and it showed 40~70% uncertainties increasing compared with the best case. In the third case, all but the new airflow meter temperature rakes were used. In this case, the uncertainty difference from the best case was less than 0.01%. The last case of Fig. 11 was the best case where all the instruments, which were the static pressure ports, new duct configuration, new airflow meter temperature rakes, cell pressure sensor and facility control, were replaced. The gross thrust uncertainty was reduced from 1.41% down to 0.22%.

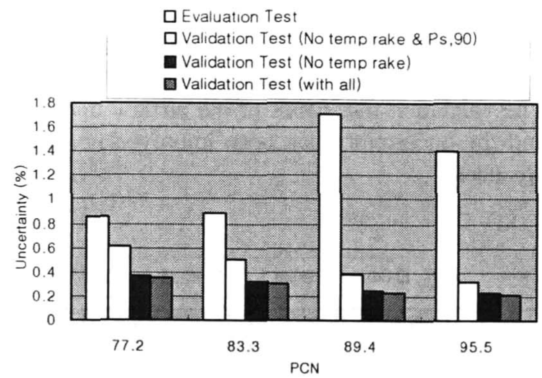

Fig. 11. Gross Thrust Uncertainty Improvement Result

Net Thrust UPC analysis from the uncertainty evaluation test is shown in Fig. 12. and the major contributors were PS,90, PS,02, P,05 and PSC. Fig. 13 shows the facility modification result of net thrust. The new airflow meter temperature rakes, cell pressure sensor and facility control method were replaced one after another. The uncertainty improvements in the best case is about 4.6 times compared with the evaluation test case.

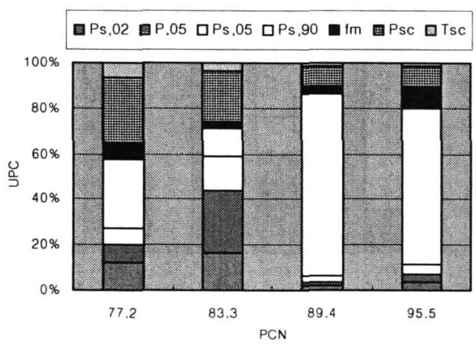

Fig. 12. Evaluation Test Result of Net Thrust

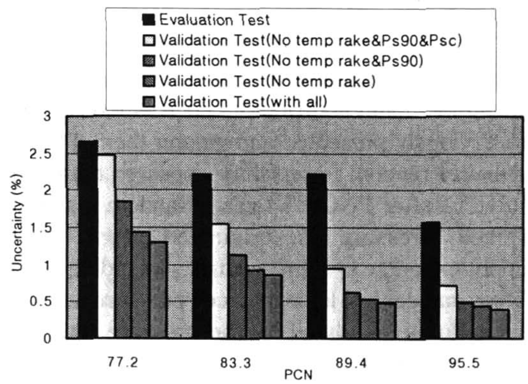

Fig. 13. Net Thrust Uncertainty Improvement Result

As indicated in Fig. 12, the random uncertainty originated from the cell pressure fluctuation took the largest part of the net thrust uncertainty. In this figure, as PCN got smaller, the net thrust uncertainty went up because of the effect of the size of the net thrust. The net thrust uncertainty was as large as the gross thrust uncertainty but near the idle condition the net thrust was relatively as small as the net thrust uncertainty. So the uncertainty ratio of these cases were relatively large. As the engine accelerated, as PCN got bigger, the gross thrust increased rapidly while the ram drag didn't increased as much as the gross thrust. So the net thrust increased while the uncertainty ratio decreased.

Specific Fuel Consumption (SFC) UPC analysis from the uncertainty evaluation test is shown in Fig. 14. Replacing the fuel flow meter and reinforcing its stand made the measurement uncertainty improved as shown in Fig.15. Because SFC depends on the net thrust directly, the uncertainty and the UPC of the SFC are very similar to those of net thrust. By this facility modification, the SFC uncertainty was improved from 2.32% to 0.55%.

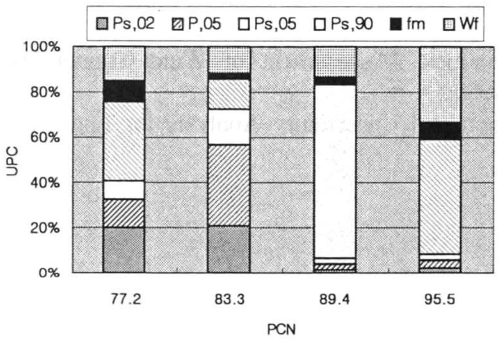

Fig. 14. Evaluation Test Result of SFC

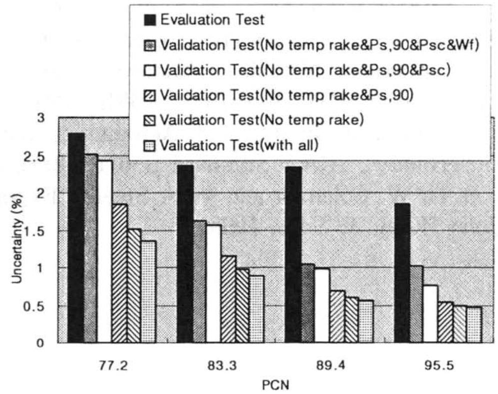

Fig. 15. SFC Uncertainty Improvement Result

Conclusions

The altitude ground test is the primary test method for aero-propulsion system and KARI launched an uncertainty improvement program for AETF. Under the various engine part loads and flight conditions, the measurement uncertainties were analyzed through the evaluation test and advanced by the facility modification. The airflow meter temperature rake, inlet duct configuration, inlet pressure transmitter accuracy, cell pressure transmitter accuracy, fuel flow meter accuracy and cell pressure control method were replaced through the facility modification and the results were quantified by the validation test. In part-load test, airflow uncertainty decreased to 0.7% and the gross thrust uncertainty was improved from 1.41% to 0.22%. Net thrust uncertainty was dominated by the cell pressure (PS,90) random uncertainty which was caused by the air supply system and the cell itself. By increasing the cell pressure accuracy and reducing the cell pressure fluctuation, the net thrust uncertainty was improved from 2.22% to 0.45%. SFC uncertainty showed the same trend as net thrust uncertainty and the uncertainty was improved from 2.32% to 0.55%. Under the various flight conditions, the major uncertainty contribution variables still dominated the overall uncertainty. In the evaluation test, the cell pressure was the largest contributor to the measurement uncertainties especially under altitude test condition. It originated from the accuracy of the cell pressure transmitter and the control of the cell pressure fluctuation. The new method for the cell pressure control was effective at sea level test conditions. But the altitude condition test results were not improved as much as the sea level condition test results. To improve the uncertainty at altitude conditions, another cell pressure control methods are under development.

References

1. Smith, R. E. and Wehofer, S., "Uncertainty of Turbine Engine Thrust in Altitude Ground Test Facilities", *Proceeding of the 29th Int. Instrumentation Symposium,* Vol.29, 1983

2. Rober, J. H., Lewis, J. H., "Engine Thrust Measurement Uncertainty", AIAA 85-1404, 1985.

3. Blevins, J. and Wagner, D., "An Uncertainty Assessment of Thrust Determination in Altitude Ground Test Facilities", AIAA 2000-0413, 2000.

4. Deasung Lee et al., "Gas Turbine Engine Components and System Performance Test Facilities in KARI," *Journal of The Korean Society for Aeronautical and Space Sciences,* Vol. 28. No. 7, 2000.

5. Minsoo Yoon et al., "Uncertainty Analysis of Altitude Performance of a Gas Turbine Engine", *J. of The Korean Society for Aeronautical and Space Sciences,*

6. Minsoo Yoon et al., "Improving the Measurement Uncertainty of Altitude Test Facility for Turbine Engines,"*J. of The Korean Society for Aeronautical and Space Sciences,* Vol. 29. No. 1, 2001.
7. American National Standards Institute/American Society of Mechanical Engineers, "Test Uncertainty", PTC 19.1-1998, ASME, 1998.
8. American Institute of Aeronautics and Astronautics, "Assessment of Wind Tunnel Data Uncertainty", AIAA Standard S-071- 1995, AIAA, 1995.
9. H. W. Coleman and W.G. Steele, "Experimentation and Uncertainty Analysis for Engineers", *John Wiley & Sons*, 1999.