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Uncertainty Analysis and ANOVA for the Measurement Reliability Estimation of Altitude Engine Test

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Abstract

The altitude engine test is carried out to measure the performance of the engine of flight vehicle at the high altitude environment prior to the flight test. During the test, The measured pressures and temperatures at various positions, air flow rate, fuel flow rate, thrust of the engine are measured. These measured values are used to calculate the representative performance values such as the net thrust and the specific fuel consumption. Hence each of the measured parameter has effects on the total uncertainty of the performance values. In this paper, the combined standard uncertainties of the net thrust and the specific fuel consumption were estimated from the uncertainties of the various measured values. Also, by estimating the repeatability and the reproducibility, the confidence levels of the altitude engine test were validated by the analysis of variation on the repeated test data by different tester groups.

Keywords: Altitude engine test; Uncertainty of measurement; Reliability of measurement; ANOVA

1. Introduction

The objective of the altitude engine test is to verify the performance and the reliability of the engine of flight vehicle before its flight test and various parameters such as pressures, temperatures, air flow rate, fuel flow rate, and thrust are measured and used to calculate the engine's representative performances, net thrust and specific fuel consumption. In 1999, Korea Aerospace Research Institute(KARI) has established altitude engine test facility(AETF) and has been testing various propulsion systems for flight vehicles. In order to increase the measurement reliability of the AETF, various measurement uncertainty analyses have been conducted in accordance with ASME or AIAA standards. (Yoon et al., 2001; Jun et al., 2002; Lee et al., 2002; Jun et al., 2004)

To represent the confidence level of the measured value, many terms including error, precision, accuracy, and uncertainty have been used and many methods have been used to evaluate them. After International Standardization Organization(ISO) issued "Guide to the Expression of Uncertainty in Measurement (ISO, 1993)," evaluation of uncertainties according to the guide has been widely used.

After AETF of KARI was accredited as a internationally certified altitude test facility, KARI has been established procedures for the uncertainty analysis in accordance with the international standard (Lee et al, 2003b). Also, the proficiency tests between different tester group have been conducted periodically. In this paper, the measurement uncertainty analysis by the ISO guide and the ANOVA(Analysis

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of Variance) were applied for the inter-tester comparison proficiency test and the results were used to verify the measurement reliability of the altitude engine test.

2. Altitude engine test

The engine used in the altitude tests was single a spool, turbojet engine. The tests were performed at standard day, sea level condition and inlet air Mach number was 0.7. During the tests, the corrected compressor rotating speed was 85 percent of the maximum rpm. The major performance parameter, the thurst and the SFC(specific fuel consumption), were measured during the test.

Figures 1 and 2 show the schematic of the altitude engine test cell. The sealed test cell consists of a thrust bed on which the engine is installed, an inlet duct through which air is supplied to the engine, and a diffuser nozzle that the engine exhaust gas is discharged through. Tests were conducted with all instruments including fuel supplying line and various sensors installed. For accurate thrust measurement, the thrust bed and the inlet duct were designed to move freely in front and in rear direction of the engine. In order to do so, a sliding duct with a slip

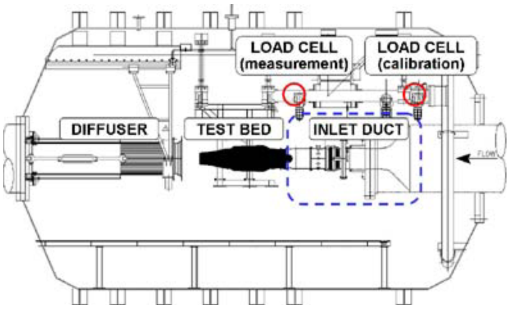

Fig. 1. AETF test cell.

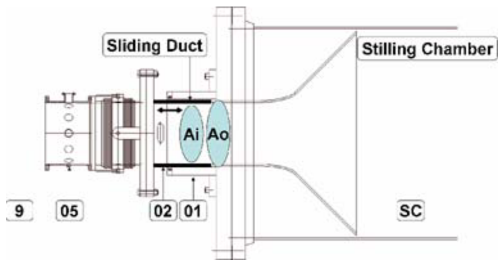

Fig. 2. Inlet duct configuration.

seal was installed in the inlet duct portion as shown in Fig. 2. The resistance by the slip seal was considered during the thrust calculation.

The gross thrust of the engine can be calculated by considering the momentum of nozzle exit gas and the force by pressure difference as expressed in Eq. (1).

$$F_G = F_M \mid F_T + W_{A01}V_{05} + (P_{S02} + P_{S9})A_{i01} + (P_{S01} + P_{S9})(A_{o01} + A_{i01}) \tag{1}$$

In Eq. F_M (1), is the force measured by load cells and F_T is the resistant force(tare load) by equipments installed on the test bed. V_{05} (air velocity at the engine inlet duct section) was calculated by the measured total pressure, static pressure, and total temperature at the section. P_S is static pressure measured at sliding duct(02), test cell(9) and fixed duct(01). A_{o01} and A_{i01} cross sectional area of fixed duct inlet and exit, respectively. W_{A01}(air mass flow rate at the inlet duct section) was measured by a Venturi flow meter (Model BVF-IF, Badger Meter, Inc.) and calculated by Eq. (2). (Jun et al., 2002)

$$W_{A01} = \frac{\pi d^2}{4} C_d Y \sqrt{\frac{2\rho \Delta P}{1-\beta^2}} \tag{2}$$

In Eq. (2), d is the throat diameter of Venturi flow meter, C_d is the discharge coefficient of the Venturi flow meter, is the expansion coefficient of the Venturi flow meter, ΔP is the pressure loss in the Venturi flow meter, and β is the area ratio of the Venturi flow meter.

The net thrust (F_N) was computed by subtracting momentum by inlet air flow from the gross thrust(F_G), as shown in Eq. (3). (Jun et al., 2002)

$$F_N = F_G - W_{A01}V_\infty \tag{3}$$

In Eq. (3), mainstream velocity, V_∞, was by total temperature($T_{T,SC}$) and total pressure at $P_{T,SC}$ stilling chamber and pressure of test cell(P_9) as shown in Eq. (4)

$$V_\infty = \sqrt{\frac{2\gamma R T_{T,SC}}{\gamma - 1}\left[\left(\frac{P_{T,SC}}{P_{S9}}\right)^{\frac{\gamma}{\gamma-1}} - 1\right]} \tag{4}$$

The fuel flow rate was measured by Coriolis flow meter(ELITE CMF050, Micromotion) and used in calculation of the specific fuel consumption(SFC) as shown in Eq. (5). (Jun et al., 2002) In Eq. (5), W_f is fuel mass flow rate and F_N is the net thrust.

$$SFC = W_f / F_N \tag{5}$$

3. Uncertainty analysis

3.1 Standard uncertainty

Though there are many factors in the measurement uncertainty, in this study, it is assumed that the major factors of the measurement uncertainty are the limit of resolution or detection of sensors and the variation of the measured data during repeated tests at the same test condition.

The uncertainties of the measured data were calculated by combining the type A and B uncertainties, as suggested by ISO(ISO, 1993). The type A uncertainty was evaluated by calculating a standard deviation of the 50 times sampled data and the type B uncertainty was calculated by sensor's known limit of resolution or detection. The standard uncertainty was computed as a root mean square of the type A and B uncertainties. Table 1 shows the uncertainty estimation of each measured parameter. The sampling rate of the test was 10 Hz and 50 samples were collected in each test. Each sampling procedure was lasted 5 seconds.

Table 1. Uncertainty estimation of variables.

variables	unit	A type	B type	u(x)
P_{AM}	Pa	1.296	3.534	3.764
ΔP_{AM}	Pa	1.156	2.036e-1	1.173
T_{AM}	K	6.547e-3	2.000e-1	2.001e-1
d	m	-	1.443e-5	1.443e-5
D	m	-	1.443e-5	1.443e-5
C_d	-	-	3.637e-3	3.637e-3
P_{S01}	Pa	1.772	3.000e+1	3.005e+1
P_{S02}	Pa	2.113	3.000e+1	3.007e+1
P_{T05}	Pa	2.843e-1	3.000e+1	3.000e+1
P_{S05}	Pa	7.985	3.000e+1	3.104e+1
P_{T05}	K	1.627e-3	1.200e-1	1.200e-1
P_{S9}	Pa	6.937e+1	3.000e+1	7.558e+1
F_M	N	2.442	1.768	3.015
A_{i01}	m2	-	2.000e-5	2.000E-5
A_{o01}	m2	-	2.000e-5	2.000E-5
P_{TSC}	Pa	3.879	3.000e+1	3.025e+1
T_{TSC}	K	1.123e-3	2.000e-2	2.003e-2
Wf	kg/hr	7.595e-2	2.100	2.101

3.2 Combined standard uncertainty

The combined standard uncertainty of the independent variables were estimated by Eqs. (6) and (7) which are know as the law of propagation of uncertainty (KOLAS, 2002).

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) = \sum_{i=1}^{N} [c_i u(x_i)]^2 \tag{6}$$

$$c_i = \frac{\partial f}{\partial x_i} \approx \frac{\Delta f}{\Delta x_i} = \frac{f(1.01x_i) - f(x_i)}{1.01x_i - x_i} \tag{7}$$

where, $u(x_i)$: standard uncertainty of input variable
$u_c(y)$: combined standard uncertainty
c_i : sensitivity coefficient

In Eq. (7), the sensitivity coefficients of the each variable were approximated as the effect on the function when the variable changed by 1%. And the combined standard uncertainty was computed as a root meas square of each multiplication of sensitivity coefficient and the standard uncertainty of the variable (KOLAS, 2002).

In this study, the combined standard uncertainty of the air flow rate was calculated from the standard uncertainty of measured parameters. And then, the air flow rate and other measured data were used as input variables in the calculation of the combined uncertainties of the net thrust and SFC.

In Eq. (2), since ρ and β are functions of pressures(P_{AM}), temperature(T_{AM}), Venturi throat diameter(d), and pipe diameter(D), the flow rate(W_{A01}) can be expressed as Eq. (8).

$$W_{A,01} = f(P_{AM}, \Delta P_{AM}, T_{AM}, D, d, C_d) \tag{8}$$

In the estimation of the uncertainty of the air flow rate, for the throat diameter and the pipe diameter, the A type uncertainty was not estimated and the B type uncertainty was assumed as the half range of the measuring limit of a Vernier calipers (0.05 mm). For the discharge coefficient, C_d, the A type uncertainty was not also evaluated and the B type uncertainty was estimated as the half range of the maximum error of 0.65% (with coverage factor, k=2 and confidence level=95.45%). Uncertainties of the other input variables were already listed in Table 1. Tables 2 shows sensitivity coefficients and uncertainties of the input variables, and calculated combined standard uncertainty of the air flow rate by Eq. (6).

Table 2. Combined standard uncertainty of W_{A01}.

input	sensitivity coeff.	uncertainty	percentage
P_{AM}	2.648e-5	3.764	0.0027
ΔP_{AM}	7.697e-4	1.173	0.0259
T_{AM}	1.139e-2	2.001e-1	0.0633
d	5.243e+1	1.443e-5	0.0052
D	4.019e-1	1.443e-5	0.0019
C_d	7.234	3.637e-3	-
W_{A01}		2.642e-2	0.3653

Table 3. Combined standard uncertainty of F_N.

input	sensitivity coeff.	uncertainty	percentage
W_{A01}	139.1335	2.642e-2	0.3653
P_{S01}	0.0105	3.005e+1	0.0220
P_{S02}	0.054640	3.007e+1	0.0224
P_{T05}	0.049441	3.000e+1	0.0214
P_{S05}	0.047436	3.104e+1	0.0234
T_{T05}	1.129692	1.200e-1	0.0380
P_{S9}	0.040467	7.558e+1	0.0746
F_M	1.000	3.015	0.4126
A_{i01}	2.273e+3	2.000e-5	0.0362
A_{o01}	3.535e+4	2.000e-5	0.0304
P_{TSC}	1.764e-2	3.025e+1	0.0215
T_{TSC}	2.729	2.003e-2	0.0063
F_N		5.0909	0.2646

Table 4. Combined standard uncertainty of SFC.

input	sensitivity coeff.	uncertainty	percentage
W_f	5.198e-4	2.101	0.6973
F_N	8.062e-5	5.091	0.2646
SFC		0.001167	0.7449

The combined standard uncertainty of the air flow rate was a B type uncertainty and the A type uncertainty of the air flow rate was a standard deviation of 50 sampled data. The standard uncertainty of the air flow rate is a root mean square of the A and B type uncertainties.

Tables 3 and 4 present sensitivity coefficients and uncertainties of the input variables, and calculated combined standard uncertainties of the net thrust and the SFC, respectively.

If the engine test condition is changed, above combined standard uncertainties analysis should be recalculated because of the characteristic of the test facility. At the different test condition, the A type uncertainties of the measured parameter would change, and that results in the change of the combined standard uncertainties.

3.3 Expanded uncertainty

Expanded uncertainty is a quantity defining an interval within which the value of the measured data is believed to lie with a high level of confidence and defined as Eq. (9) (KOLAS, 2002).

$$U = k \cdot u_c(y) \tag{9}$$

where, U : expanded uncertainty
k : coverage factor

To find the coverage factor, the effective degree of freedom of the combined standard uncertainty is required and that is calculated by following Welch-Satterthwaite equation (KOLAS, 2002).

$$\nu_{eff} = \frac{u_c^4(y)}{\sum_{i=1}^{N} \frac{[c_i u(x_i)^4]}{\nu i}} = \frac{u_c^4(y)}{\sum_{i=1}^{N} \frac{u_i^4(y)}{\nu_i}} \tag{10}$$

where, ν_{eff} : effective degree of freedom
ν_i : degree of freedom of $u(x_i)$

The degree of freedom, ν_i, in Eq. (10) is evaluated by different way depending on the method of the evaluation of the uncertainty of input variable, $u(x_i)$. If $u(x_i)$ is evaluated by the type A evaluation of uncertainty, the degree of freedom of the sample population become ν_i. If $u(x_i)$ is computed by the type B evaluation of uncertainty, ν_i is found by Eq. (11) (KOLAS, 2002).

$$\nu_i \approx \frac{1}{2}\frac{u(x_i)^2}{\sigma(u(x_i))^2} \approx \frac{1}{2}\left[\frac{\Delta u(x_i)}{u(x_i)}\right]^{-2} \approx \frac{1}{2}(\frac{100}{R})^2 \tag{11}$$

Tables 5, 6, and 7 shows the calculated degrees of freedom of the air flow rate, the net thrust, and the SFC, respectively.

With the calculated effective degree of freedom of the each input variable, the expanded uncertainty can be calculated. If the effective degree of freedom is sufficiently larger than 100, the coverage factor, , can be assumed as k=2 (KOLAS, 2002). Then the expanded uncertainties of the net thrust and the SFC can be evaluated as Eqs. (12) and (13), and the results correspond to 0.53% and 1.49% of the measured data, respectively.

Table 5. Degree of freedom of W_{A01}.

DOF	variable	A type	B type
ν_i	P_{AM}	49	200*
	ΔP_{AM}	49	200*
	T_{AM}	49	200*
	d	N/A	**
	D	N/A	**
	C_d	N/A	**
ν_{eff}	W_{A01}	3307427	

* : with 95% of confidence level of the calibration
** : with 100% confidence level with assumption of rectangular distribution

Table 6 Degree of freedom of F_N.

DOF	variable	A type	B type
ν_i	W_{A01}	49	3307427
	P_{S01}	199	200*
	P_{S02}	199	200*
	P_{T05}	2099	200*
	P_{S05}	199	200*
	T_{T05}	399	200*
	P_{S9}	49	200*
	F_M	49	200*
	A_{i01}	N/A	**
	A_{o01}	N/A	**
	P_{TSC}	199	200*
	$T_{T,SC}$	199	200*
ν_{eff}	W_{A01}	315	

* : with 95% of confidence level of the calibration
** : with 100% confidence level with assumption of rectangular distribution

Table 7. Degree of freedom of SFC.

DOF	variable	A type	B type
ν_i	W_f	49	200*
	F_M	N/A	315
ν_{eff}	SFC	258	

* : with 95% of confidence level of the calibration

$$U_{F_N} = k \cdot u_{F_N} = 2 \times 5.090953 = 10.181906 \quad (\nu_{eff,F_N} = 315 \gg 100) \tag{12}$$

$$U_{SFC} = k \cdot u_{SFC} = 2 \times 0.001167 = 0.002334 \quad (\nu_{eff,SFC} = 258 \gg 100) \tag{13}$$

3.4 Verification of the calculated expanded uncertainty (Monte carlo simulation)

Since the law of propagation of uncertainty used in above analysis was first order approximation of the Taylor expansion and the sensitive coefficient was calculated by difference equation instead of differential equation, it is expected that there is error in the analysis (Lee et al, 2003a).

Monte Carlo Simulation(MCS) is a method that can simulate the effect of the varying input on the output. In the MCS, if the probability distributions of the varying input is defined, the likelihood of the output can be calculated (Decisioneering, 2005). Compared with other uncertainty analysis methods, the MCS can model complex equations and if the number of simulation is large enough, accurate results can be acquired because there is no internal error source such as the Taylor expansion or the approximation in the calculation of the sensitive coefficient (Papadopoulos and Yeung, 2001).

In this study, the MCS for the air flow rate, the net thrust, and the SFC was conducted and the results was used to verify the combined standard uncertainties calculated in the previous sections.

In the MCS, a commercial software(Crystal Ball 7, Decisioneering) was used and the same standard

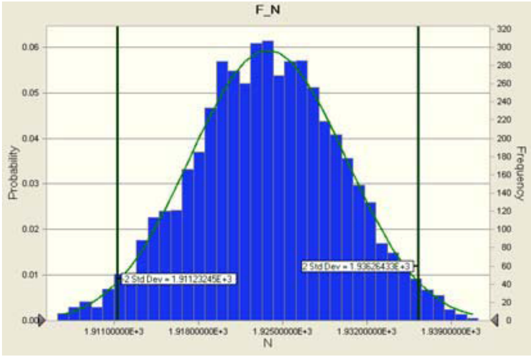

Fig. 3. MCS prediction of F_N.

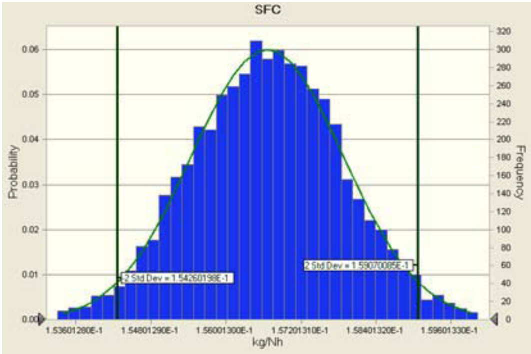

Fig. 4. MCS prediction of SFC.

Table 8. Validation of the uncertainty assessment.

Performance	Uc	MCS	error
F_N	0.26%	0.33%	0.07%
SFC	0.74%	0.77%	0.03%

deviations and limits of resolution of sensor of the input variables as previous uncertainty analysis were used. And the distributions of the input variable were assumed as a normal or a rectangular distribution depending on the characteristic of the uncertainty of the input variable. The maximum number of simulation was set as 5,000 and the simulation was terminated if the 95% confidence level was satisfied (Decisioneering, 2005).

Figures 3 and 4 show the MCS results for the net thrust and the SFC, and the shape of the result is similar with that of normal distribution.

Table 8 present the comparison of the combined uncertainty by the uncertainty analysis and the standard deviation by the MCS for the net thrust and the SFC. Results show that both results agree with errors less than 0.1% and the errors could be caused by the approximations used in the uncertainty analysis.

4. ANOVA

4.1 Inter-tester comparison proficiency test

The precision of the measurement system is decided by the repeatability and the reproducibility of measured data. The repeatability is a variation of the measured data during repeated measurement by same person and same measuring device. The reproducibility is a change in the measured data when the measurement is conducted by different person with same measuring device (Pyzdek, 2003).

In the altitude engine test, the major factor of the non-reproducibility is the controls of the test facility, the data acquisition system, and the engine operating condition. In order to reduce those factors, the test procedure was standardized and inter-tester comparison proficiency test has been conducted regularly. In the inter-tester comparison proficiency test, each tester group conducted 21 tests at the predefined test condition and the results were analyzed by the two-way ANOVA in order to ensure the repeatability of each tester group and the reproducibility between tester groups.

Table 9. Proficiency test result (conventional).

Team	A	B
Average	5316.6*	5304.3*
Std. deviation	53.0*	51.4*

* Measured data were multiplied by arbitrary number due to se-curity reason

Table 10. Two-way ANOVA result (conventional).

Source	DF	SS	MS	F	P
Team	1	172	172	1.10	0.307
Sample	20	8974	449	2.86	0.012
Error	20	3140	157		
Total	41	12286			

4.2 ANOVA for the inter-tester comparison proficiency test

The analysis of variance, or more briefly ANOVA, measures the total variation in the data and the total variation is partitioned into two parts. One is variation from errors and the other is variation from the factor (Devore, 2000).

In the inter-tester comparison proficiency test which estimates the repeatability and the reproducibility, test sample and tester group were selected as independent variables and the two-way ANOVA was performed.

Tables 9 and 10 show the result of ANOVA for the inter-tester comparison proficiency test between two tester groups. In the tables, degree of freedom(DF), sum of squares(SS), mean square(MS), the ratio of the mean square for a factor to the mean square for error(F) and the type I error(P-value) are shown. In the proficiency test, the test condition was obtained and maintained by automatically controlling of the AETF. The pressure of the test cell, which is quite sensitive to the pressure oscillation between the ejecting gas of an engine nozzle and the diffuser, was controlled by the automatic control valves installed on the inlet duct and the exhaust duct.

When the ANOVA test with a significance level of 0.05 was applied to the results in Table 10, the null hypothesis for the test group was not rejected and that for the sample was rejected. In case of automatic control of the test facility, the test condition of the facility changes continuously to meet the target condition. Therefore relatively large standard deviation of the measurement to the measured value of about 1% was obtained as shown in the Table 9 and that means the repeatability of the test was not good.

Table 11. Proficiency test result (new procedure).

Sampling	Team A	Team B
Average	5543.4*	5518.2*
Std. Deviation	15.8*	27.4*

* Measured data were multiplied by arbitrary number due to security reason

Table 12. Two-way ANOVA result (new procedure).

Source	DF	SS	MS	F	P
Team	1	744.4	744.4	18.78	0.000
Sample	20	1433.7	71.7	1.81	0.097
Error	20	792.6	39.6		
Total	41	2970.7			

While the standard deviation of the measurement was large, the difference of the mean values by the two tester groups was relatively small and that means the reproducibility was good.

In order to reduce the standard deviation of the measurement, new test procedure was obtained by adding manual controlling process to the conventional automatic control procedure. After the test condition of the facility reached the target condition by the automatic control system, the facility was controlled manually in order to reduce the small oscillation of the test condition and the control valves were adjusted to meet the target condition precisely prior to the measurement.

Table 11 and Table 12 shows the result of ANOVA for the proficiency test with modified test procedure. When the ANOVA test with a significance level of 0.05 was applied to the results in Table 12, the null hypothesis for the sample was not rejected and that for the tester group was rejected. Although the standard deviation of the measurement was improved by about 0.5%, the reproducibility became worse because the difference of the mean values was relatively large while the difference of the standard deviation of the sampling was smaller.

The results of ANOVA for the inter-tester comparison proficiency test show that the repeatability and the reproducibility were not im-proved at the same time with current test procedures. It is recommended to develope new test procedure which can improve both the repeatability and the reproducibility by properly combining automatic and manual test procedures. That will be next step of this study.

5. Conclusions

In this paper, the uncertainty analysis and ANOVA for the major engine performance measurements were conducted in order to ensure the measurement reliability in the altitude engine test facility of KARI. Based on the analyses, major founding are as following:

1. Evaluating method for accuracy and precision of the altitude engine test were presented.
2. Uncertainty analysis showed that the measurement uncertainties for the net thrust and the SFC were about 0.5% and 1%, respectively
3. ANOVA results showed that the improvement of the repeatability and the reproducibility of the results by changing control method could not be achieved at the same time. Development of new test procedure is recommended.

The analysis methods used in this paper are expected to be utilized in developing test procedures for the repeatable, reproducible measurement results in the altitude engine test.

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