Preflight Evaluation of Landing Performance by Computer Simulation

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ABSTRACT

In the ALFLEX experiment, the automatic flight control system can be modelled precisely and so it is possible to simulate the motion of the vehicle relatively accurately. However, there are discrepancies between simulated and real systems due to model errors, and it is necessary to clarify the effect of these errors in order to predict landing performance and to verify that the vehicle will land successfully. Because of the power of modern computers, it was possible to perform simulation analyses which incorporated the results of various system tests as they were carried out at Woomera Airfield in Australia. Landing performance, including the effects of various model errors, was investigated by Sensitivity Analysis, the Root Sum Square (RSS) method and Monte Carlo simulation. The simulation results were used in deciding whether or not to proceed with the automatic landing tests. These methods and simulated results are described here. Furthermore, the simulation results are compared with actual flight data. Computer simulation is shown to be effective and useful for the preflight evaluation of landing performance.

1. Introduction

In the ALFLEX experiment, the motion of the vehicle is controlled by an onboard computer with no provision for remote control. (In the event of an emergency, the vehicle can be forced to drop to the ground by remote control.) So, the vehicle motion heavily depends on the installed control law. It is necessary to evaluate flight safety and landing performance before the automatic landing flight trials. For the evaluation, computer simulation was used from release of the vehicle to landing .

The automatic flight control system can be mathematically modelled precisely. With vehicle and environmental mathematical models, the motion of the vehicle can be computed. However in real system, there are many uncertain factors, expressed as modeling errors shown in Fig. 1.

Usually, it is difficult to identify the magnitude of these errors, and some of them might degrade landing performance. Despite these factors, the vehicle must fly safely and its landing performance meet the requirements.

First, the effect of aerodynamic model error on landing performance was investigated, because aerodynamic model errors, in particular, are considered to be an uncertain factor. The purpose of the analysis is to extract influential aerodynamic model errors prior to the hanging flight test in which the test for aerodynamic parameter estimation was carried out. Next, the results of the hanging flight tests and other various system tests were incorporated in the simulation analyses. Involving all modeling errors as shown Fig. 1, the Root Sum Square (RSS) method and Monte Carlo simulation were used to evaluate total landing performance. By the RSS method, total deviation of landing performance is derived by accumulating the variance of landing performance due to each model error. Furthermore, the effect of various combinations of model errors was analyzed by Monte Carlo simulation.

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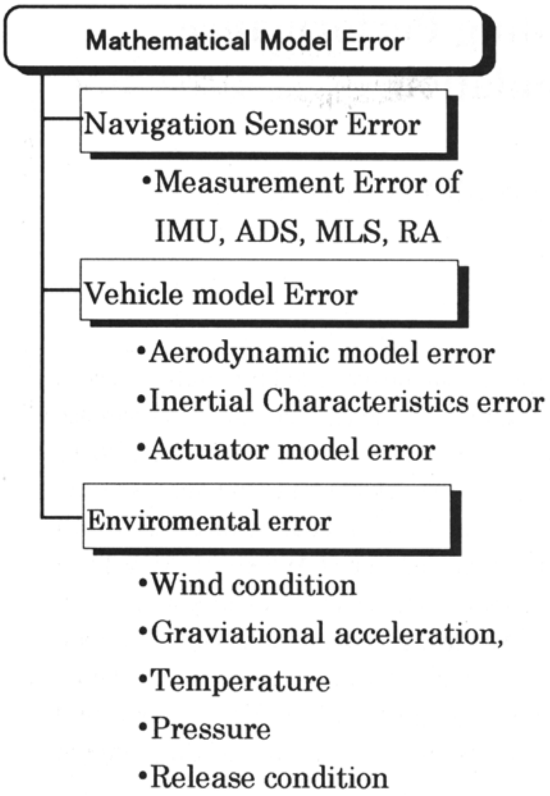


Fig. 1 Model error

In these simulation analyses, the vehicle motion from release to landing must be computed many times for each model error or for combination of model errors. Thanks to recent dramatic increases in the power of computers, it was possible to perform all of these simulation analyses before the automatic landing flight test. As a result, flight safety and landing performance were confirmed prior to the automatic flight tests. Table 1 shows the touchdown requirement of state variables.

Table 1 Touchdown requirement

	GNC Requirement
Longitudinal	$\lvert X_{\max} - X_{\min} \rvert \le 450$ (m) $\dot{Z} \le 3.0$ (m/s) $V_{nom} - 8 \le V_{EAS} \le V_{nom} + 8$ (m/s) $\Theta \le 23.0$ (deg)
Lateral	$\lvert Y \rvert \le 18.0$ (m) $\lvert \Phi \rvert \le 10.0$ (deg) $\lvert \Psi \rvert \le 8.0$ (deg)

V_{nom} **: Nominal value**

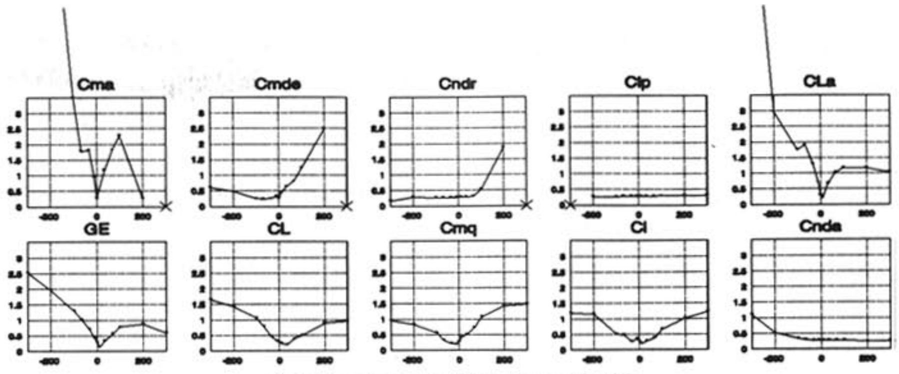
2. Sensitivity Analysis for aerodynamic model errors

In this sensitivity analysis, space shuttle data which shows the maximum difference between wind tunnel test data and actual aerodynamic characteristics, was basically used as the model error of ALFLEX vehicle. The space shuttle data is assumed to be statistically equivalent to 3 σ -value of model error, but it is still uncertain whether the error values can be applied for the ALFLEX vehicle. For this reason, the analysis range of aerodynamic model error was extended to 9 σ -value. The results of sensitivity analysis are shown in Fig. 2; the horizontal axis shows model error value: "100" corresponds to 3 σ -value, so "300" corresponds to 9 σ, and "0" shows the nominal case (no model error). Cross mark, "x", in the graph means the landing failed.

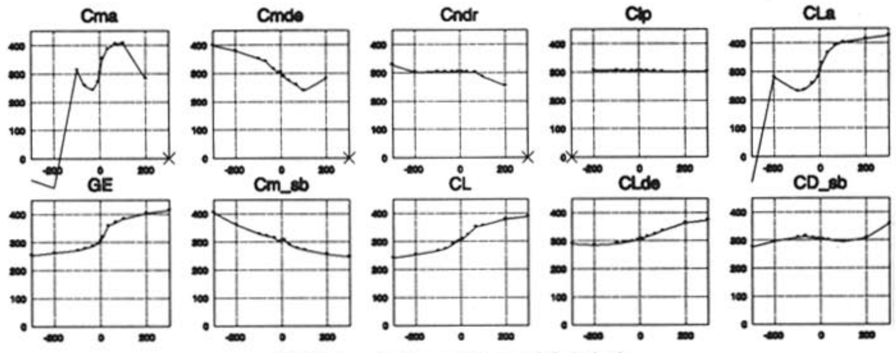
From Fig. 2, it is found that landing failed if model errors of Cm_α, $Cm_{\delta e}$, $Cn_{\delta r}$, or Cl_p have 9 σ deviation. However, landing performances meet the requirement of Table 1, when each model error deviates within $\pm 3\sigma$ -value. Fig. 2 (c) and (d) show that the lateral motion has sufficient margin for the requirements; the sensitivity of landing performance against aerodynamic model errors is relatively small. Fig. 2 (a) and (b) show that there are some aerodynamic model errors which significantly affect the landing performance in the case of longitudinal motion. The model errors of Cm_α, $Cm_{\delta e}$ and CL_α are significant. When these parameters have model errors, landing performance such as touchdown position or touchdown sink-rate might be affected significantly. These model errors were derived by aerodynamic characteristics estimation using hanging flight test data. As a result, it was verified that actual model errors do not significantly affect landing performance. After that, total simulation analysis including all modeling errors shown in Fig. 1, was performed by the Root Sum Square (RSS) method and Monte Carlo simulation.

3. Root Sum Square (RSS) method

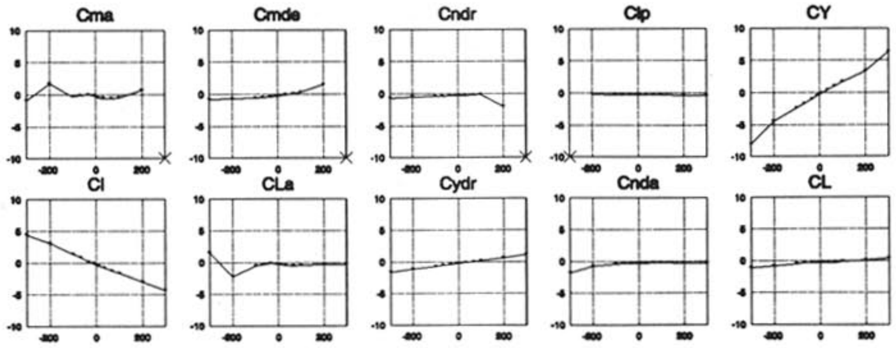
In order to evaluate landing performance incorporating the effect of all model errors, the Root Sum Square method was applied. This method is frequently used in Japanese rocket launch projects. In this method, total variance of landing performance is



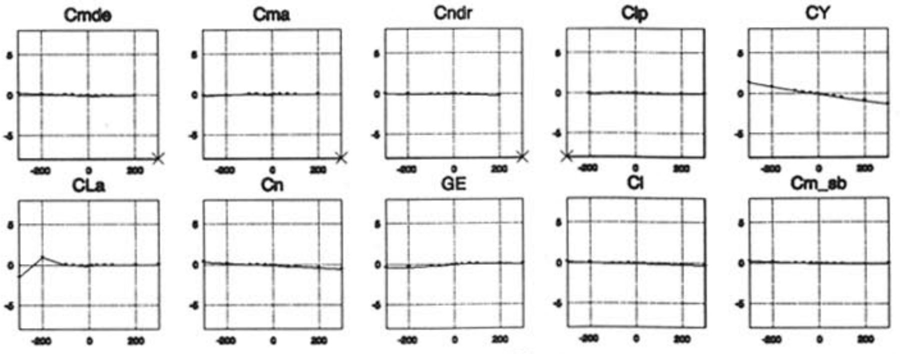
(a) Touchdown Sink-Rate (m/s)



(b) Touchdown X-position(m)



(c) Touchdown Y-position(m)



(d) Touchdown Ψ (deg)

Fig. 2 The influence of aerodynamic parameter

derived by accumulating the variance of landing performance due to each model error. The result of the RSS method is reliable provided that the following two criteria are met:

- There is a linear relationship between a change in model error and the resulting deviation of landing.
- Model errors are independent of each other.

Because the real system does not meet these conditions, the following processing was used here so that the RSS method can be applied. The deviation of landing performance from the nominal due to each model error of 3 σ-value was derived by simulation. $3\sigma_i$ represents 3 σ-value of "i" th model error. $y(3\sigma_i)$ and $y(-3\sigma_i)$ represent landing performance due to $3\sigma_i$ and $-3\sigma_i$ model error, respectively. Then $y_{3\sigma i}$, which represents the deviation of landing performance from the nominal due to the 3 σ-value of "i" th model error, is determined as Eq. (1).

$$y_{3\sigma i} = \sqrt{\frac{\{y(3\sigma_i) - y_{\_nom}\}^2 + \{y(-3\sigma_i) - y_{\_nom}\}^2}{2}} \tag{1}$$

$y_{\_nom}$ represents nominal value. It is the simulation result when no model error is incorporated. When landing performance changes linearly against the value of model error, $|y(3\sigma_i) - y_{\_nom}|$ and $|y(-3\sigma_i) - y_{\_nom}|$ are the same value. The RSS value shows total deviation of landing performance against all 3 σ-value of model error. It is expressed as;

$$y_{RSS} = \sqrt{\sum_i y_{3\sigma i}{}^2} \tag{2}$$

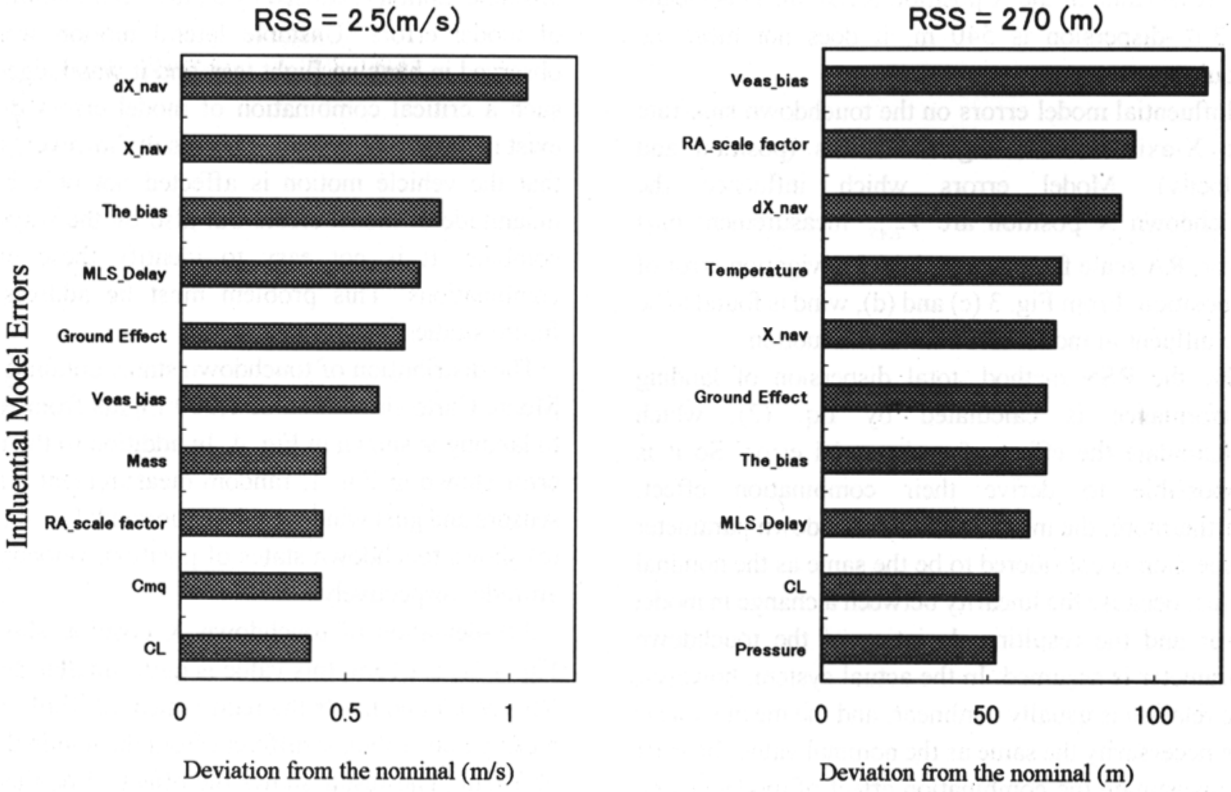
By the RSS method, Eq. (2) represents the total 3 σ-deviation of landing performance. In this analysis, the model errors shown in Fig. 1 are included and its number is more than 90. The given wind condition is a 45 deg diagonal head-wind and the power is a maximum-designed-steady-wind. The wind condition was chosen so that it wind affects both longitudinal and lateral motion. The results of hanging flight test and various system tests were incorporated and model error value was modified. The touchdown states of nominal case, in which no model error is included, are shown in Table 2. Simulation model as well as model error incorporated the test results. Mainly aerodynamic model and time delay of control system were modified. For this reason, the values in Table 2 are a little different from the values described in other papers or reports.

Table 2 Touchdown States (Nominal)

State Variable		Touchdown Value
Z-dot	(m/s)	0.5
V_{EAS}	(m/s)	52.5
X	(m)	303
Θ	(deg)	13.7
Y	(m)	-0.4
Ψ	(deg)	-0.2
Φ	(deg)	0.5

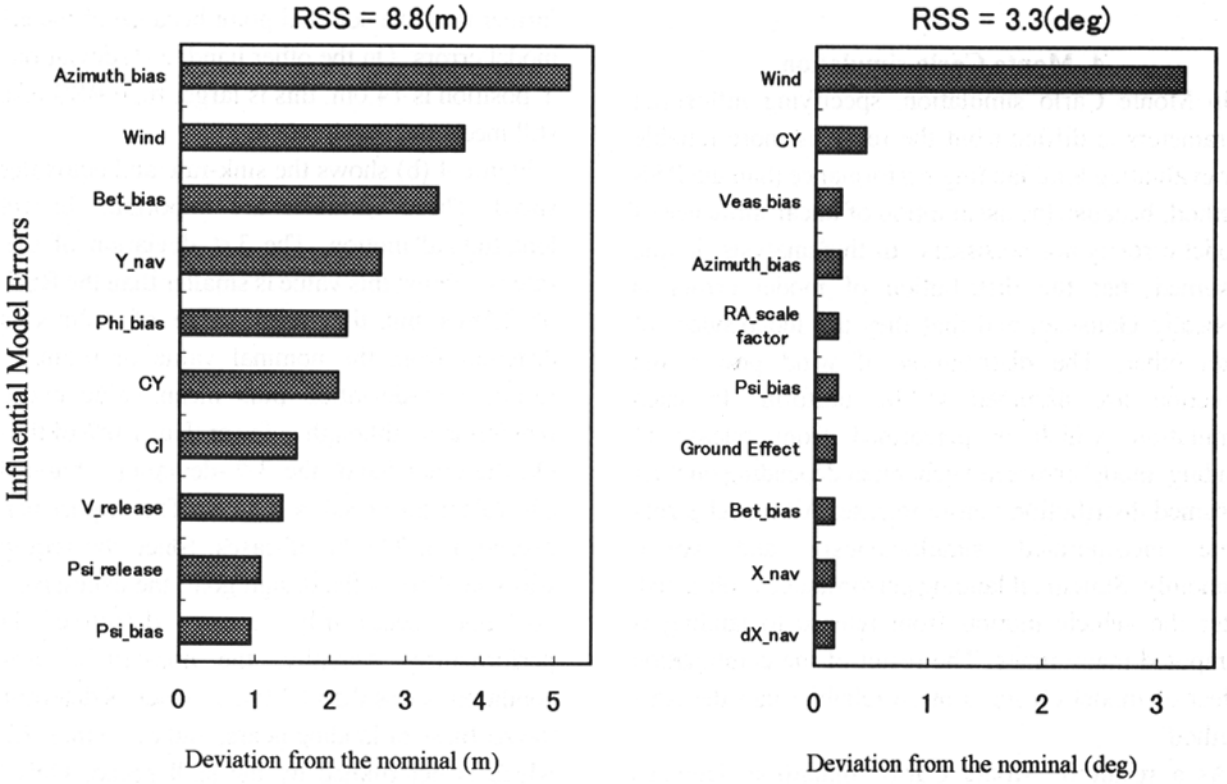
The result of RSS analysis is shown in Fig. 3. These four graphs show influential model errors on touchdown parameter of sink-rate, X position, Y position, and Ψ. In Fig. 3, the 10 most influential model errors are shown for each touchdown parameter. The horizontal axis represents the value calculated by Eq. (1), which expresses the deviation of landing performance against each model error. And the RSS value calculated by Eq. (2) is shown at the top of each graph. From the result of Fig. 2, model errors of Cm_α, $Cm_{\delta e}$ and CL_α were influential. But they are not apparent in Fig. 3. This is because these aerodynamic model errors were estimated by using the hanging flight test data, and the result was incorporated to the mathematical model.

From the graph Fig. 3 (c) and (d), it is clear that the effect of model error on the touchdown parameter related to the lateral motion is small and landing performance has sufficient margin for the requirement. RSS values are also small enough and meet the requirements. On the other hand, longitudinal touchdown parameters, sink-rate and X position are shown in Fig. 3 (a) and (b). The RSS value of sink rate is 2.5 m/s, and the nominal value is 0.5 m/s. The sink-rate barely meets the requirements of Table 1, but



(a) Touchdown Sink-Rate

(b) Touchdown X-position



(c) Touchdown Y position

(d) Touchdown Ψ

Fig. 3 Root-Sum-Square(RSS) Method

the RSS value of the X position is 270 m. This means ±3 σ-dispersion is 540 m; it does not meet the requirement.

Influential model errors on the touchdown sink-rate are X-axis initial navigation errors (position and velocity). Model errors which influence the touchdown X position are V_{EAS} measurement bias error, RA scale factor error, initial navigation error of X position. From Fig. 3 (c) and (d), wind is found to be the influential model error on lateral motion.

By the RSS method, total dispersion of landing performance is calculated by Eq. (2), which accumulate the effect of each model error. So it is impossible to derive their combination effect. Furthermore, the mean value of touchdown parameter dispersion is considered to be the same as the nominal value, because the linearity between a change in model error and the resulting deviation of the touchdown parameter is assumed. In the actual system, however, the relation is usually nonlinear, and the mean value is not necessarily the same as the nominal value. In order to investigate the combination effect of model errors, Monte Carlo simulation was performed. The result is compared with the RSS method in the next section.

4. Monte Carlo simulation

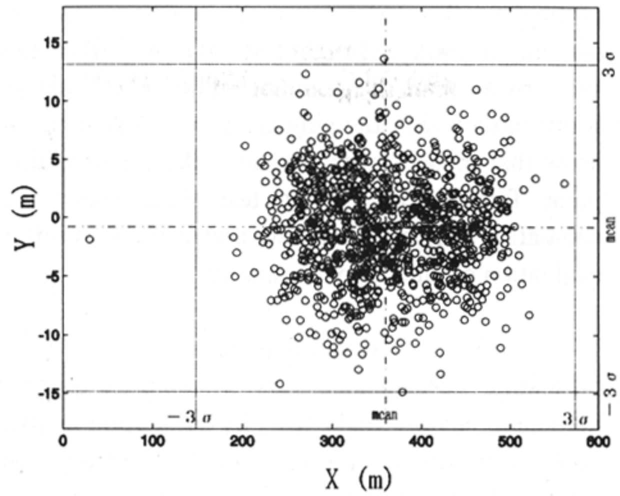
In Monte Carlo simulation, specifying influential parameters is difficult but the result is more reliable for evaluating total landing performance than the RSS method, because the assumption of linear influence of model error is not necessary. In this analysis, it was assumed that the distribution of model errors is basically Gaussian and that they are independent of each other. The distribution of wind power and direction are assumed to be uniform. In each simulation, which is performed from release to landing, model errors are generated depending on their assumed distribution before release. All model errors were incorporated simultaneously and varied randomly. Statistical landing performance is obtained, after the vehicle motion from release to landing is computed many times. The result of the combination effect of model errors is more reliable than the RSS method.

As a result of Monte Carlo simulation, landings failed in about 2.0% of cases. In these cases, lateral motions became unstable just after release. This unstable motion is caused by a particular combination of model errors. Unstable lateral motion was not observed in hanging flight test, and it was judged that such a critical combination of model errors did not exist in the actual system. This result, however, shows that the vehicle motion is affected not only by the magnitude of model errors but also by the ways they combine. It is not easy to identify these critical combinations. This problem must be addressed in future studies.

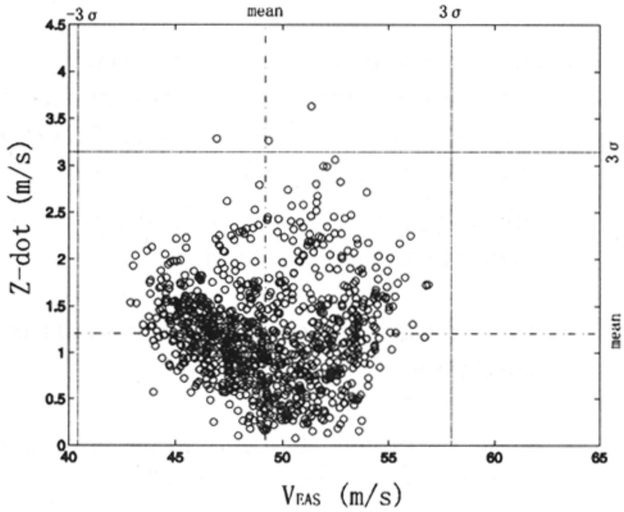
The distribution of touchdown states obtained from Monte Carlo simulation of 1,000 flights from release to landing is shown in Fig. 4. In addition to the model error shown in Fig. 1, random measurement error of sensors and gust wind were incorporated. Fig. 4 (a) (b) (c) shows touchdown states of position, velocity, and attitude, respectively.

3 σ-deviation of touchdown X position shown in Fig. 4 (a) is 213m; this value is quite smaller than the RSS result and meets the requirement of Table 1. The mean value, 360m, is different from the nominal value of 303m. The result shows the effect of nonlinearity between model error and touchdown X position. It is found that the touchdown X position tends to be farther than the nominal point because of the effect of model errors. On the other hand, 3 σ-deviation of the Y position is 14.0m; this is larger than RSS result but still meets the requirement.

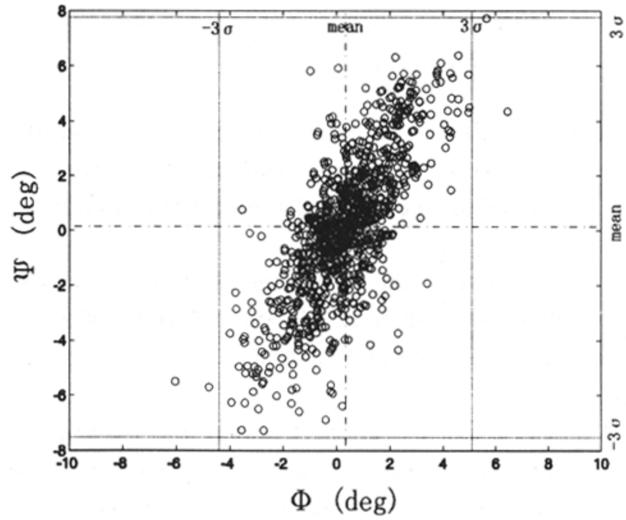
Figure 4 (b) shows the sink-rate and equivalent-air-speed. These variables are important for vehicle's longitudinal motion. The 3 σ-deviation of the sink-rate is 1.9m/s; this value is smaller than the RSS result of 2.5m/s but the mean value of 1.2m/s is also different from the nominal value of 0.5m/s. As a result, 3 σ-deviation plus mean value exceed the requirement, although is fewer than 1.0% of the cases. On the other hand, the 3 σ-deviation of touchdown equivalent-air-speed is 8.8m/s. The requirement was exceeded in 3～4% of cases. Since the requirement was specified as the design goal, the excessive values do not necessarily mean defective landing performance. Actually, the non-critical air-speed condition is less than 62.0m/s, which is determined by the stiffness of landing gears, and more than 42.0m/s, which is determined by the stall speed. Only 0.1～0.2% of the cases exceeded these limitations.



(a) Touchdown Point

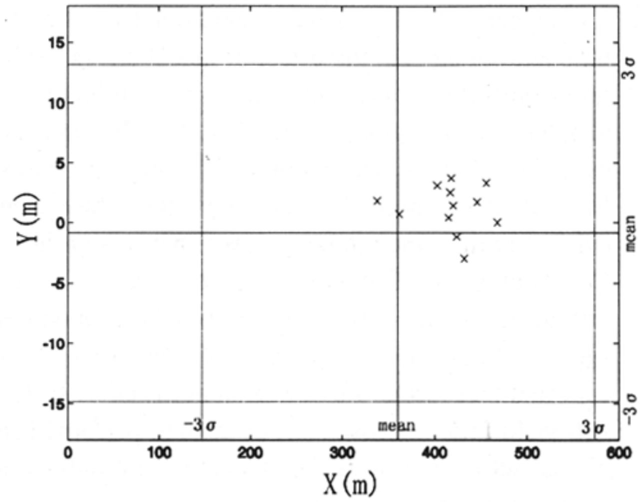


(b) Touchdown Velocity

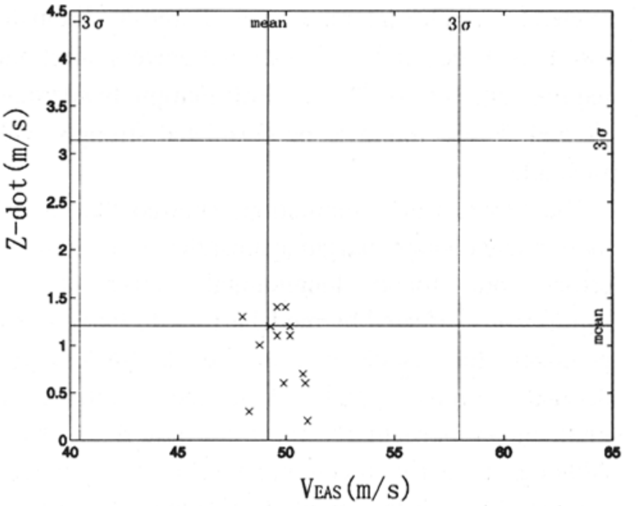


(c) Touchdown Attitude

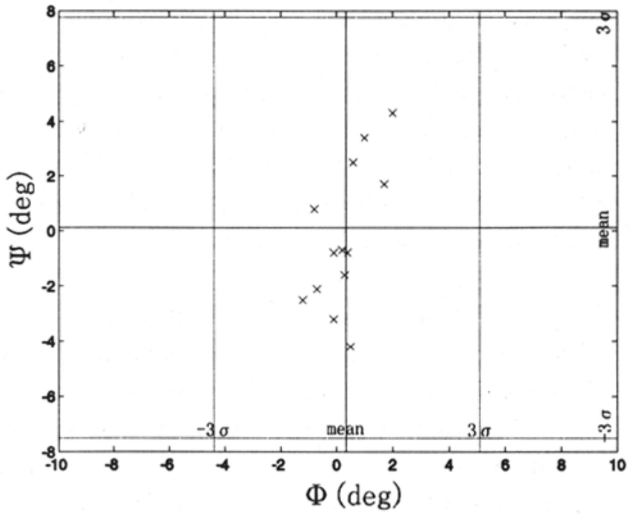
Fig. 4 Monte Carlo Simulation



(a) Touchdown Point



(b) Touchdown Velocity



(c) Touchdown Attitude

Fig. 5 Flight Data

Considering these results, longitudinal motion has little margin against the effect of model errors. Sink-rate 4.0m/s is out of requirement, but is considered not to affect the airframe so significantly. The sink-rate exceeded 4.0m/s in about 0.5% of the cases. Equivalent-air-speed does not meet the requirement either, but the simulation result was not so significant for landing performance, as mentioned above. Furthermore, the GNC system has been modified several times, and is considered advanced. It is expected that further modification of the GNC system will yield little improvement of landing performance. These factors were considered, and then the automatic landing test was executed.

Figure 4 (c) shows the touchdown parameters related to vehicle's lateral motion, Φ and Ψ. From the result, 3σ-deviation of both parameters meet the requirement, though Ψ has a little margin. In addition, Φ and Ψ are found to be correlated strongly with each other.

The Monte Carlo simulations showed that lateral motion had enough margin against the effect of model errors, but found longitudinal motion to be significantly affected by model errors. In longitudinal guidance, the vehicle is controlled to track a pre-defined nominal path. Open-loop control is predominant particularly in the pre-flare flight phase. Although closed-loop command exist, this open-loop command makes the longitudinal motion sensitive to model errors. On the other hand, because lateral guidance is implemented only by closed-loop which works to decrease the deviation from the reference, lateral motion has stiffness against model errors. The 2.0% of unstable lateral motion cases were due to closed-loop stability characteristics. In a closed-loop system, motion suddenly becomes unstable when the system exceeds the stability limit.

5. Comparison with Flight Data

Fig. 5 (a)～(c) shows touchdown parameters of all 13 automatic landing tests. The graph corresponds to Fig. 4. The Monte Carlo-derived mean value and 3σ-deviation are also shown in Fig. 5 to allow comparison of the flight test result with the simulation result.

Fig. 5 shows that all flight data is in the $\pm 3\sigma$-ranges predicted by Monte Carlo simulation. In particular, the touchdown X positions of both simulation result and flight test data are farther down the runway than the nominal value. The flight test result agrees with the simulated result. Both results show that model errors tend to make the touchdown point farther. The flight test data shows that simulation analysis is effective and useful for preflight evaluation of landing performance.

6. Conclusion

Landing performance was investigated prior to automatic landing flight tests by simulation analyses such as sensitivity analysis, the RSS method, and Monte Carlo simulation. The major points are as follows:

(1) For aerodynamic model errors which are a particularly uncertain factor, sensitivity analysis was performed considering the model error range of $\pm 9\sigma$. Particularly Cm_α error was found to influence landing performance, and the error was verified by hanging flight test.

(2) RSS method was used to determine influential model errors.

(3) Monte Carlo simulation derived the distribution of landing performance statistically.

(4) The results of Monte Carlo simulation and the RSS method were compared, and the differences were quantified.

(5) The flight test data agreed with the preflight simulation analysis; simulation analysis was found to be effective for preflight evaluation.

Furthermore, the following simulation analyses were also performed at Woomera Airfield in order to confirm the successful landing.

- The effect of release position and magnitude of control surface exciting command were investigated by simulation analysis in order to confirm the landing performance of each planned test case.

- Real wind data, which was measured 1.5 hr before the automatic landing test, was used for simulation analysis. The simulation result was used as one of the data for go or no-go decision.

- Error models which incorporated the results of hanging flight test or other system test were modelled. Then the effect of those errors were investigated by simulation. Specifically, aerodynamic error, RA measurement error, MLS measurement error, and ADS measurement error were considered.

From the simulation analysis, the RSS method is useful for specifying influential error parameters, whereas Monte Carlo simulation can statistically predict the total landing performance accurately and is appropriate for analyzing the combination effect of model errors and the non-linearity between model error and landing performance. The application of these simulation techniques proved very effective in evaluating landing performance prior to actual automatic landing test.

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