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# Flight Testing of ALFLEX Guidance, Navigation and Control System

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## ABSTRACT

Automatic Landing Flight Experiment (ALFLEX) is a research program conducted by the National Aerospace Laboratory and National Space Development Agency of Japan in order to investigate automatic landing technology for the future development of a Japanese unmanned reusable reentry space vehicle. Due to the bare airframe's instability and the landing performance requirement, the flight control for the space vehicle's horizontal landing is one of the key technologies. The ALFLEX vehicle, a 37% sub-scale model of a planned reentry space vehicle, and a flight experiment system were developed. The ALFLEX vehicle is equipped with up-to-date avionics, including a high performance flight control computer. The vehicle performed 13 landing flight trials successfully at Woomera, Australia, in 1996. It satisfied the predetermined performance and the flight test result has demonstrated technological readiness for the future reentry space vehicle's automatic landing. This paper introduces an overview of the guidance, navigation and control system (GNC), and discusses results of the flight testing.

*Keywords: Reentry space vehicle, automatic landing, flight testing*

## 1. INTRODUCTION

The US Space Shuttle is a unique operational winged reentry space vehicle, and it has proved technological accomplishment in atmospheric reentry flight and horizontal landing. 1) to 6). In Japan, the National Aerospace Laboratory (NAL) and National Space Development Agency of Japan (NASDA) are collaboratively conducting research experiment programs in order to develop key technologies for the future development of a Japanese unmanned reentry space vehicle. ALFLEX, Automatic Landing FLight EXperiment which aims at development of technology for the space vehicle's subsonic flight control and automatic landing, is one of these programs. OREX, Orbital Reentry Experiment, successfully completed its flight experiment in 1994 for reentry aerodynamic heating and heat resistant structures research. HYFLEX, Hypersonic Flight Experiment, was conducted in parallel with ALFLEX for hypersonic aerodynamics and thermal protection system research. 7) After the completion of these flight experiment programs, H II Orbiting Plane Experiment (HOPE-X) program was started in 1996. As shown in Fig. 1, the vehicle will be launched by an H IIA launch vehicle from NASDA Tanegashima Space Center and it will land horizontally on an island in the Pacific Ocean after orbital flight. The vehicle mass will be approximately 10 tons. The vehicle's basic design is under way, and a flight experiment is scheduled around 2003. Adding the functions of orbital mission capability and reusability, HOPE-XA is planned as a next technology development program after HOPE-X. These technologies will be extended to future space vehicles, such as a reusable launch vehicle and space plane.

The ALFLEX, which is the objective of the present paper, was designed in order to demonstrate fundamental technologies for the space vehicle's automatic landing. The program commenced in 1993. It took two and a half years to design, develop and test the vehicle and experiment system. The vehicle performed 13 landing trials at Woomera, Australia in the winter of 1996. Fig. 2 is a photograph taken from a chase helicopter for the first landing.

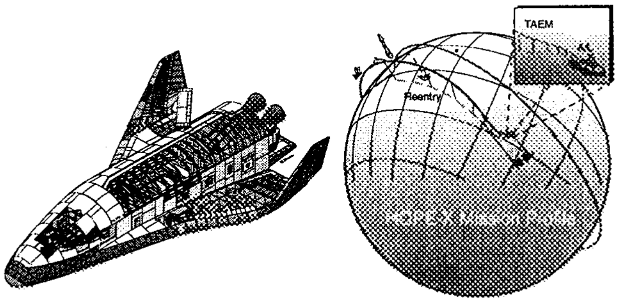

**Fig.1 HOPE-X and its mission profile**

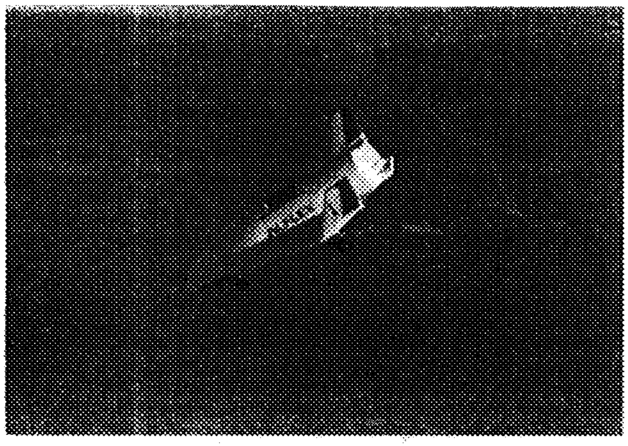

**Fig. 2 ALFLEX vehicle after the release (photograph)**

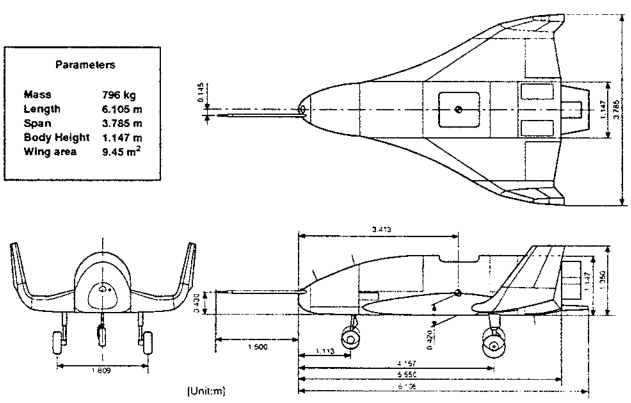

**Fig. 3 Three views of ALFLEX vehicle**

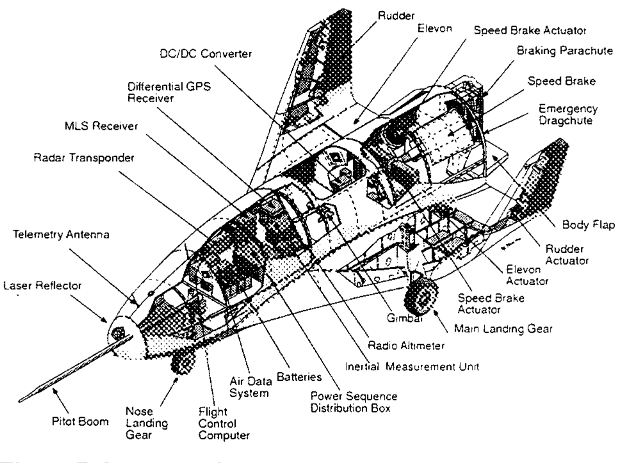

**Fig. 4 Primary onboard equipment**

The program's purpose consists of the following. (1) to establish and demonstrate automatic landing system technology and design method for the guidance, navigation and control (GNC) system; (2) to obtain low-speed flight characteristics and to evaluate aerodynamic data estimated by wind-tunnel tests; (3) to develop flight experiment technology with a scale model. This paper addresses the guidance, navigation and control system, which is the first and most important purpose of the experiment. The ALFLEX vehicle's bare airframe has various adverse characteristics in flight control. For example, the vehicle is unstable in longitudinal and lateral-directional motions and its lift-by-drag ration is very low. These problems are products of compromise with critical aerodynamic and structural requirement in other flight phases, such as hypersonic, supersonic and transonic. Furthermore, the performance requirement for landing is the most critical compared with other flight phases, because the length of the landing strip is so limited and wind disturbances are unavoidable at low altitudes. Since the vehicle is unmanned and autonomous, the flight control system should demonstrate the final performance from the first landing trial. Recent technological advances in flight control for fighters, helicopters, and missiles have overcome similar design challenges. Through the ALFLEX GNC development and flight testing, we have demonstrated and verified the capability of the automatic flight control system for the space vehicle's landing. Before discussion of the flight testing, this paper gives an overview of the vehicle and experiment system, and its GNC system. Technical data and experiment results have already been published in detail. 8)-14)

## 2. ALFLEX VEHICLE AND EXPERIMENT SYSTEM

### 2.1 Scale model experiment

ALFLEX is a scale model experiment of a future 15-ton-class space vehicle. The vehicle airframe is designed to be dynamically similar to the space vehicle studied as the Japanese future program H II Orbiting Plane (HOPE) in 1992. The GNC system for ALFLEX is also designed to be as similar as possible. Fig. 3 shows three views of the vehicle, and Fig. 4 shows the primary onboard equipment. The model's scale of length is 37%. In order for the HOPE space vehicle to land on a 3000m class runway, the ALFLEX is designed to land safely on a runway of 1000 m length. According to the similarity rule in model experiment, where acceleration and mass density are equal for the real and model vehicles, the model's time scale is 60.8%, and the model's velocity scale is 60.8%. The ALFLEX vehicle's mass is 796 kg, which corresponds to the HOPE vehicle's landing weight of 15.7 tons.

### 2.2 Onboard equipment

The ALFLEX vehicle is equipped with similar avionics to the future HOPE vehicle in order to realize the scaled model experiment. Special hardware, however, has not been developed in the

ALFLEX program. Instead, commercially proven avionics and off-the-shelf components are used. An exception is a pseudo-satellite differential GPS system (DGPS), for which the NASDA Tsukuba Space Center developed an onboard receiver and ground system for future applications. Due to the experiment' s objective and for simplicity, all components are single channel and there is no redundancy except for an emergency flight termination system. Fig. 5 shows primary components of the vehicle and experiment system. General features of components related to the GNC system are as follows.

1) FCC, Flight Control Computer: A single chip DSP(TMS320C30) is used for flight control. The minor cycle of calculation is 80 Hz, and the major cycle is 10 Hz. The computer calculates control command and inertial navigation in each minor cycle and it generates guidance command in each major cycle. Data transfer for the navigation avionics such as inertial and air data sensors uses a 1553B digital data bus.
2) IMU, Inertial measurement unit: The ALFLEX vehicle is equipped with a strap down inertial measurement unit containing three axes ring laser gyros and accelerometers. The IMU has the same accuracy as those used in aircraft. The output update cycle of the IMU is 80 [Hz], which is the same as the FCC's minor cycle, but they are asynchronous with each other.
3) MLS, Microwave landing system: An MLS which is equivalent to those used in civil aviation has been developed. It measures azimuth and elevation angles from each ground station. Distance Measuring Equipment is not provided. The azimuth signal is receivable on the runway for the vehicle's ground roll navigation. The accuracy requirement follows the ICAO standard.
4) RA, Radio Altimeter: A pulse type radio altimeter well-proven in civil aviation, is used. The RA data are utilized below 200 m, while the altitude range is below 762 m. The analog RA output signal is digitized by the FCC's A/D converter.
5) ADS, Air Data Sensor system: ADS probe is installed on the top of a 1.5 m nose boom in order to minimize the effect of vehicle, or the position error. The Pitot-probe has five holes, one on each of the five planes of the quadrangular prismoid, pressures of which are measured by the Air Data Computer (ADC) at a sampling rate of 32 Hz. The ADC calculates the static pressure, dynamic pressure, equivalent air speed, angle of attack and side-slip angle by using stored data, which has been calibrated with the window tunnel test.
6) DGPS, Differential Global Positioning System: A pseudo-satellite type differential global positioning system was developed for the experiment. The pseudo-satellite ground station transmits correction data for the pseudo-range of GPS satellites, and it works as GPS satellites on the ground, which increases the accuracy especially in a poor GDOP (Geometrical Dilution Of Precision) condition. Since the system was not fully proven when the ALFLEX program started, the main purpose of the onboard DGPS is to obtain engineering data for future missions, and it is not used as a flight critical component.
7) Actuator subsystem: The ALFLEX vehicle has elevons, rudders and speedbrakes for aerodynamic control. Electric motor actuators drive the control surfaces. The dynamics of the elevon and rudder actuator systems can be roughly approximated by a 2nd order system with an undamped natural frequency of more than 12 Hz. The vehicle's nose landing gear has a steering actuator system and the main landing gears have an anti-skid brake system for ground roll. The vehicle has a drag chute for deceleration after the touch down.
8) Telemetry system: The flight data which include the sensors' output, status of flight condition and the results of calculation are transmitted to the ground station through the PCM encoder. The transmission's performance is 81.92 [kbps] (80 [Hz cycle], 128 [word/frame], 8 [bit/word]). The ground station stored all the telemetry data, which were analyzed after the flight experiment.

### 2.3 Experiment system

Since the ALFLEX vehicle is unpowered, it is lifted by a helicopter. The mother helicopter has onboard control/monitor equipment that can change the vehicle's experiment mode. The vehicle's flight control system function is checked by selecting the experiment mode in the hanging flight configuration. Ground facilities, such as MLS and DGPS ground stations, flight data monitoring system, laser tracker and tracking radar systems, support the experiment. The flight data monitoring system on the ground checks the vehicle's status and stores all the

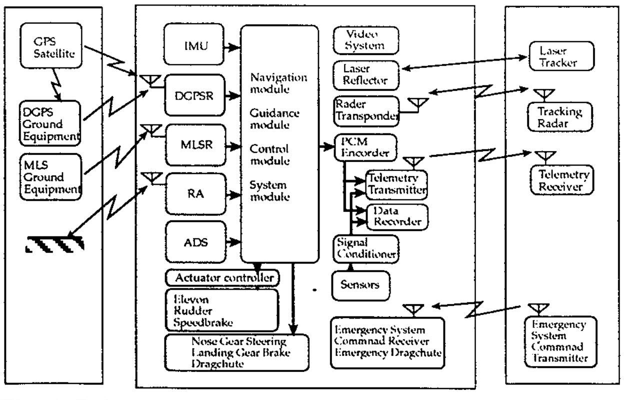

Fig. 5 Primary components of ALFLEX system

telemetry data. The laser tracker provides reference data for the vehicle position to evaluate the navigation system. The tracking radar provides position data for flight safety. Fig. 6 shows the sequence of the experiment.

## 3. GUIDANCE, NAVIGATION AND CONTROL SYSTEM DESIGN

### 3.1 Design requirement and design condition

The experiment's design goal is safe automatic landing on a 1000 m runway. Quantitative performance requirements are defined for the GNC system design, where the landing performance is mainly evaluated by variables at the touch down point. Table 1 shows the requirements for the ALFLEX GNC system.

The GNC system was designed to satisfy the requirements under wind and turbulence conditions, which are transformed with the similarity rule from the conditions in MIL-F-9490D specification (the US military specification for automatic flight control systems). The maximum steady wind at 6.1 m above the ground is 25 kt, 15 kt, 10 kt, for head, cross and tail winds, respectively. Further study, such as design margin analysis and consideration of shear wind, was conducted in order to enhance the landing performance.

### 3.2 Reference trajectory

The ALFLEX vehicle is released at an altitude of 1500m from a helicopter with a speed of 46.3m/s (90kt) EAS. The release altitude is determined in order to achieve an equilibrium flight condition on the glide slope, where approximately 500m altitude will be lost before accelerating to the glide slope speed of 84m/s EAS. The steep glide slope angle is 30 degrees. Figure 7 shows the vehicle's reference trajectory.

**Table 1. Landing performance requirement for the GNC system**

| Evaluation point | Requirement |
|---|---|
| Touchdown | |
| Position | X: >0m Y: ±18m |
| Velocity | Ground speed: <62m/s<br>Airspeed: 51.5±8m/s<br>Sink rate: <3m/s |
| Attitude | Pitch angle : <23 degrees<br>Bank angle : ±10 degrees、<br>Yaw angle : ±8 degrees |
| Ground roll | Y: ±20m |
| Stop point | X: <1000m |

X,Y, and Z present the vehicle's position with the runway coordinate system, the origin of which is at the runway threshold and on the center line. The XY plane is on the local horizon, the Z axis is downward and the X axis is forward on the center line.

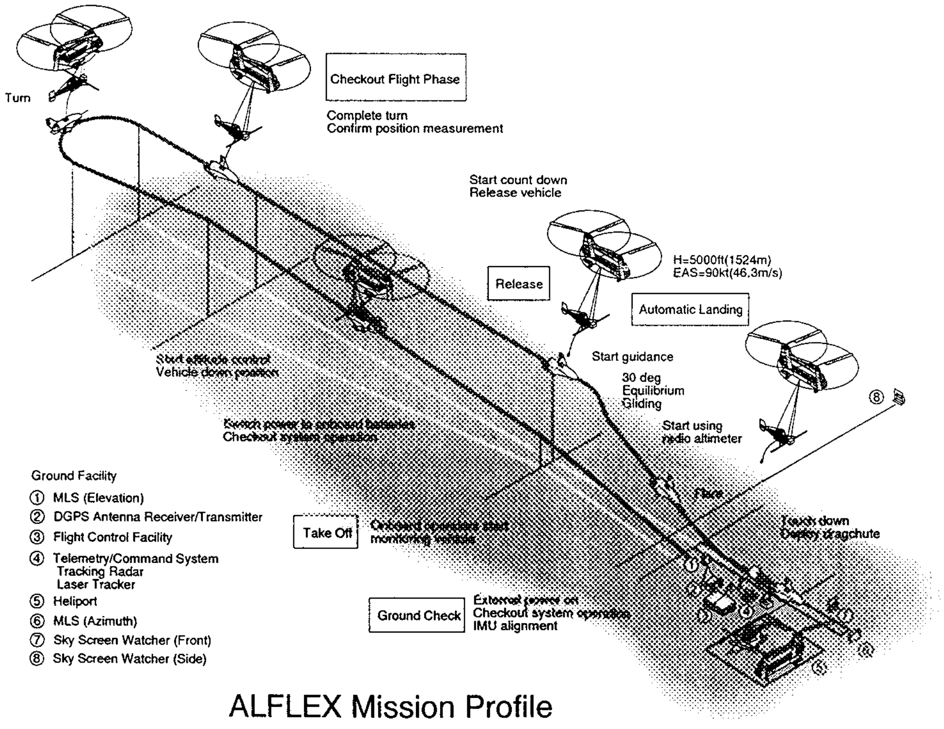

**Fig. 6 Sequence of landing flight experiment**

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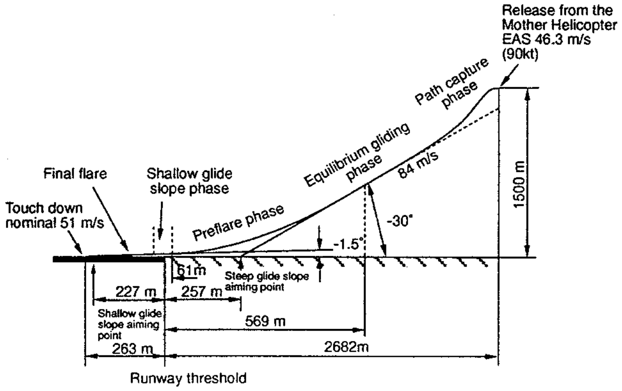

Fig. 7 Reference trajectory

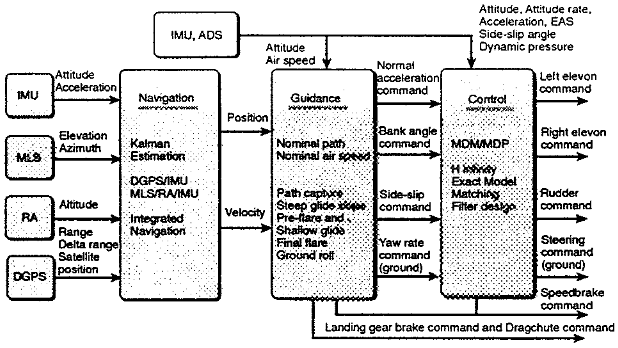

Fig. 8 GNC system function block diagram

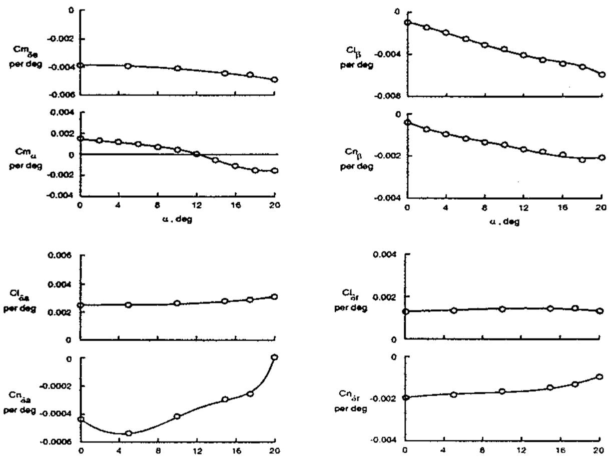

Fig. 9 Stability and control derivatives

### 3.3 GNC system

Fig. 8 shows a function block diagram of the ALFLEX's GNC system. Flight Control Program (FCP) was developed to realize the GNC function.

For the navigation, FCC calculates position and velocity estimates by inertial navigation, up-dating by appropriately selecting landing navigation aids, such as DGPS, MLS and RA. Two navigation algorithms have been developed. One is DGPS integrated inertial (DGPS/IMU) navigation, and the other is MLS/RA integrated inertial (MLS/RA/IMU) navigation. Since the DGPS/IMU navigation is an on-going research subject, real time estimation results are used only in a non-flight-critical phase, i.e. the navigation algorithms are switched from DGPS/IMU to MLS/RA/IMU at the time of 20 seconds prior to the release of the ALFLEX vehicle. The 3 sigma accuracy goal of the DGPS/IMU navigation is 25m and 0.5m/s for the position and velocity estimates of each axis. In the free flight, the MLS/RA/IMU navigation provides the vehicle's position and velocity. The MLS/RA/IMU navigation's 3 sigma accuracy goal defined at the touch down position, is 60m, , 8m, , and 0.8m for down range, lateral deviation and altitude positions, respectively, and 2m/s, 0.5m/s, and 0.5m/s for each velocity.

Guidance calculates a reference trajectory and compares it with the vehicle's position and velocity estimated by the navigation. It generates guidance commands in order to reduce the errors in longitudinal and lateral positions. For the guidance command calculation, the vehicle's landing flight is divided into several phases: glide path capture phase, steep glide slope phase, pre-flare and shallow glide slope phase, final flare phase and ground roll phase. Guidance algorithms are designed for each phase. The longitudinal guidance commands are normal acceleration and speedbrake angle. Appropriate open-loop normal acceleration commands that depend on the vehicle's state are added to the feedback control in order to minimize the vehicle's path error from the reference trajectory. For the lateral guidance, the bank angle is a command. Since the ALFLEX's reference trajectory on the horizontal plane is a straight line, a double integrator can approximate the lateral translational motion, therefore a relatively simple PID controller with appropriate limiters generates the lateral guidance command.

The ALFLEX vehicle has unstable flight dynamics in both longitudinal and lateral-directional motions, and its flight characteristics change with angle of attack. Figure 9 shows stability and control derivatives. Under these adverse properties in flight control, the control system should perform quick responses to commands in order to obtain the final landing accuracy. The higher the feedback gain, the more vulnerable the system is to structural flexibility. The trade-off between performance and robustness is one of the most critical issues in the ALFLEX GNC design. The multiple delay model and multiple design point (MDM/MDP) technique developed at NAL introduces a fundamental control law and the H infinity exact model matching ($H_{\text{infinity}}$ EMM) design method enhances robustness of the fundamental control law by using a high order filter, which shapes the frequency response of the open loop transfer

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function. The ALFLEX longitudinal and lateral-directional control laws were realized by 5th and 10th order filters, respectively.

## 4 PRELIMINARY TESTS AND SIMULATION ANALYSIS

Prior to the landing trials, the GNC system's function and performance were examined, first on the ground and next by the preliminary hanging flight. In parallel with checking the components and subsystems, computer simulation analysis was conducted to predict the total performance. Listed below are major points in the preliminary tests.

### 4.1 Ground vibration test and control law design modification

The ALFLEX lateral-directional control experienced a series of modifications to cope with a control-structure coupling problem after the vehicle's vibration test. For the ALFLEX lateral-directional motion, quick response to the lateral-directional guidance command is required in order to suppress the lateral deviation due to wind and turbulence. Aileron and rudder surfaces control the vehicle's bank and side-slip angles. The vehicle's structural flexibility, however, limits the response performance. The elevons and rudders of ALFLEX do not have static balance and they easily excite flexible modes. The rudder excites a boom's oscillatory mode (15Hz), which is fed back through the side-slip angle measurement. The rudder also excites a tip-fin bending and wing anti-symmetrical bending mode (22Hz), which is fed back through the roll rate signal from IMU located on the body's center line. Elevon actuator's support system's flexibility results in elevon actuator dynamics (16Hz) of low damping ratio, which affects the roll mode stability margin. Efficient filter design is essential. The ALFLEX employed two design techniques, MDM/MDP and H-infinity EMM, which aim to optimize the performance and robustness of the linear flight control system.

Figure 10a is a simple block diagram of the lateral-directional control to show the mechanism of control-structure coupling. Figure 10b shows the closed -loop vulnerability against flexible modes' effects. The upper figure is a gain diagram of the rigid body model's closed-loop system, in which the input is roll angle including roll rate and the output is rudder command. In the lower figure, the input is side-slip angle and the output is rudder command. Control laws' version numbers, such as 3.1, 3.2.7, 3.4.4, indicate the control law's modification history. Law 3.4.4 is the final version used for the landing experiment. Figures clearly show that the control laws were modified to decrease the high-frequency gain against flexible mode's uncertainty. Figure 10c shows the control performance of rigid body motion. The filter's change in the high frequency does not have significant effects on the response to commands except for cross-coupling. H-infinity EMM method was helpful in designing the sophisticated high order filter.

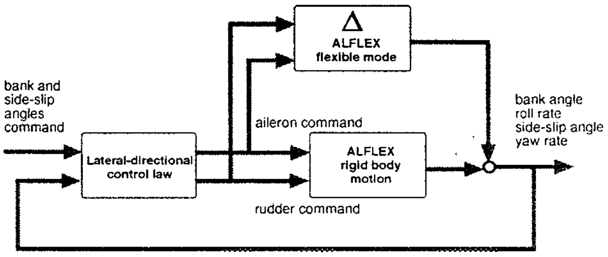

Fig. 10a Lateral-directional control block diagram

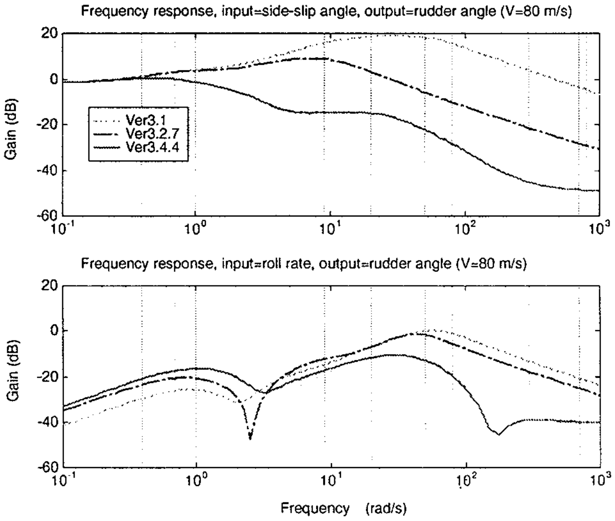

Fig. 10b Lateral-directional control law modification (closed-loop frequency response)

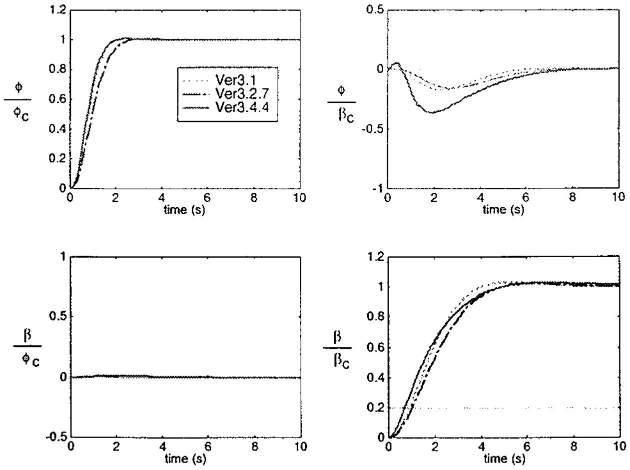

Fig. 10c Lateral-directional control law modification (resonse to command)

### 4.2 Preliminary hanging flight test

Five degrees of freedom hanging (5DOF) flight test is a unique testing technique designed for ALFLEX to confirm the flight control system function's validity. It remarkably enhanced the probability of success for the first landing. Figure 11 shows the perspective view of the configuration. The ALFLEX vehicle has a gimbal at the center of gravity, and the hanging equipment has a winch to extend the towing cable. Since the flight dynamics of this 5DOF configuration is close to those of the free flight in the high frequency range, the same flight control law is applied to evaluate the stability and performance. Actually, since the stability margin in the 5DOF configuration is more critical than the free flight, the preliminary flight test results convinced us of the flight control system's stability. The onboard flight control program has a function to generate various patterns of command, such as alpha and beta sweeps, and M-sequence disturbance, in order to evaluate the flight control system's function, aerodynamic characteristics and closed-loop system's stability in this configuration.11)12)

### 4.3 Simulation analysis

Evaluation by numerical flight simulation played very important role in the ALFLEX program. Since the vehicle is automatic, or not controlled manually, flight simulation is far more simple than those for man-in-the-loop systems. Uncertainties, such as sensors' error, aerodynamic characteristics, actuator dynamics, environmental conditions and so on, are modeled by parameters. This leads to about one hundred parameters. By assuming each parameter's probability distributions and disturbances' stochastic properties, it is possible to estimate the stochastic landing performance. Root sum square (RSS) analysis was conducted to estimate the total error from the nominal and each parameter's contribution. Sensitivity analysis was also conducted to predict safety margins against each parameters' variation. The RSS analysis could pick up influential parameters on the final landing performance, and the results were helpful for efficiently conducting ground tests and preliminary hanging flight tests. Longitudinal aerodynamic characteristics estimation is a typical example. The pitching moment coefficient vs. angle of attack is the most influential parameter on the touch down performance, and it is necessary to reduce the coefficient's variation in order to ensure the first landing trial's success. Using data from the preliminary hanging flight test, the longitudinal aerodynamic characteristics were estimated, and they could reduce the probability of exceeding the sink rate requirement at touchdown to an acceptable level.

Since the RSS analysis is an approximate estimate based on the assumption of linearity, Monte Carlo simulation was conducted to give a more reliable estimate for probability distribution of variables related to landing performance. The first landing trial could be conducted with confidence based on the extensive number of Monte Carlo simulations.13)14) Figure 11 is an example of the landing performance, which shows the significance of Monte Carlo simulation analysis. The result was obtained prior to the first landing trial. Among 1000 cases of simulation, 13 cases do not satisfy the requirement in this example. Comparing the flight test results, Fig. 14, which will be discussed in the next chapter , it could be recognized that the reality was a quite probable one among many predicted cases. The Monte Carlo simulation analysis could give a probability estimate of the final mission achievement, which should be maximized by the flight control law design. This clear design goal contributes to efficiency of its design process. The concept is the same as that proposed by Stengel et al, where they called it "stochastic robustness" of the flight control system.15) The concept and simulation analysis using recent advanced computational resources will be more important in the HOPE-X program.

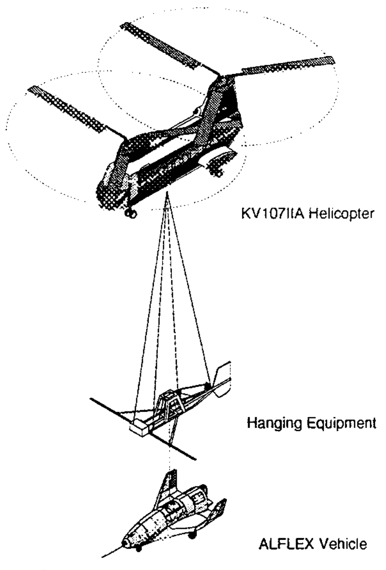

**Fig. 11 Five degrees of freedom hanging flight configuration**

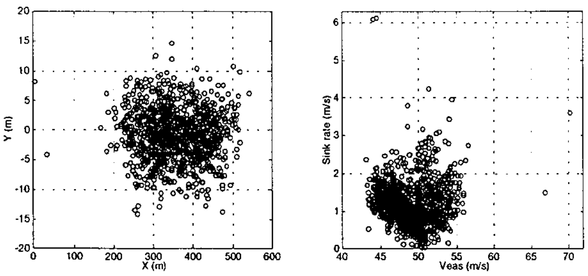

**Fig. 12 A result of Monte Carlo simulation**

## 5. AUTOMATIC LANDING TRIALS AND FLIGHT TEST RESULTS

The vehicle and experiment system were transferred to Woomera, Australia, for landing flight trials in March 1996. On July 6, 1996 it performed the first landing trial with success, and it completed 13 landings in total on August 15, 1996. We conducted all the scheduled flight experiments without changing flight control programs and parameters. The following are major flight test results and their discussions.

### 5.1 Navigation performance

Off-line path reconstruction with Laser Tracker's position data and onboard IMU was used as a reference for navigation system evaluation. Fig. 13 shows the obtained navigation performance. DGPS-IMU navigation was evaluated at the switching point from DGPS-IMU to MLS-RA navigation in the hanging flight prior to the release. The errors in three directions are approximately half of the requirement. MLS-RA navigation was evaluated at the touch down point. Longitudinal and lateral errors, or errors in X and Y directions, are well within the accuracy requirement, especially lateral accuracy is quite satisfactory owing to the MLS performance. On the other hand, the altitude and its rate errors are over the requirement due to the RA performance and terrain condition. Since this unsatisfactory performance was predicted in the preliminary navigation evaluation by the hanging flight configuration, simulation analysis was conducted to ensure the margin in the navigation requirement.

Off-line analysis for DGPS-IMU navigation in the landing flight was also conducted, and it reveals that the accuracy of the DGPS-IMU integrated navigation is equivalent to those obtained from the real-time navigation in the hanging flight. The off-line analysis indicates that the MLS will not be essential for future landing experiments.

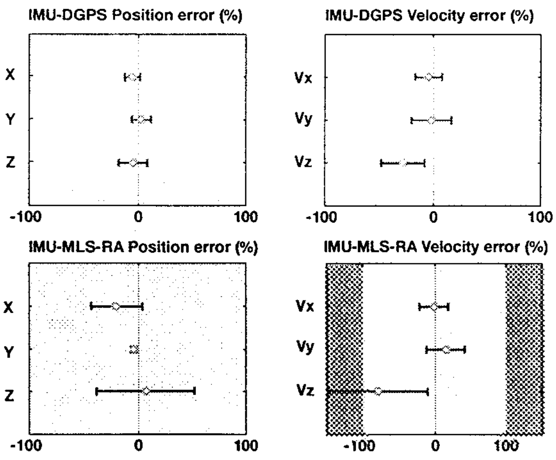

**Fig. 13 Navigattion performance (mean and variance normalized by 3 sigma requirement)**

### 5.2 Landing trials performance

The ALFLEX vehicle performed 13 landing trials with the same flight control program. Except for the first two trials, however, every landing trial contains intentional disturbances, such as off-setting the release point and/or M-sequence test input onto a control surface's command. Since the intentional disturbances are stabilized before the preflare, landing performances are mainly affected by a wind condition and navigation error. Fig. 14 shows principal landing performances obtained from 13 flights. In each figure, circles correspond to each flight trial and I bar symbols show variances of 13 flight data. Full scales of each figure correspond to the design requirement. The figure shows clearly that in all thirteen landing trials the performance satisfied the requirement with appropriate margin and the controlled variables' variations from trial to trial were small.

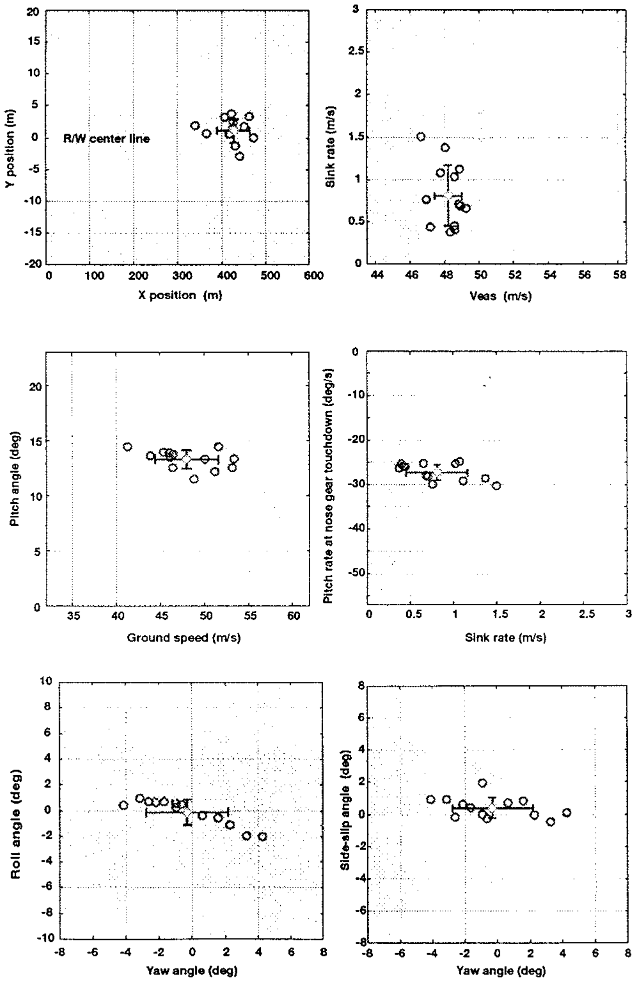

**Fig. 14 Landing performance**

### 5.3 Longitudinal guidance and control in pre-flare phase

As shown in the flight test results, Fig. 14, the longitudinal touchdown point (X position) is nearly 150 m apart from the predicted nominal point. Longitudinal guidance accuracy in the pre-flare phase is one of the most important technical points in the reentry space vehicle's landing. In order to track the curved trajectory, longitudinal guidance command consists of feedback and feedforward signals, i.e. feedforward or open-loop guidance command that is calculated from the path curvature and vehicle's velocity is added to the PID type feedback guidance command. Although the reference trajectory has a shallow glide after the pre-flare, where the feedforward command is not necessary, it is very short, i.e. the duration time is normally only one second, and therefore, path deviation in the pre-flare phase should be suppressed as much as possible for the safe landing.

All the thirteen flight trajectories were higher than the reference path at the end of the pre-flare, where the amount of each error was from 1 m to 5 m. Fig. 15 shows the trajectories of the landing trials. The altitude error introduced the floating tendency before the touch down. Analysis conducted after the completioin of the flight tests identified the cause of this phenomenon. From the analysis, error sources, such as MLS measurement delay time error and air data sensor's velocity error, can explain the cause of the trajectory error.

### 5.4 Off-set release performance

Among the 13 landing flight tests, 7 cases of off-setting the release point were tested, with 2 cases of lateral off-set, 4 cases of longitudinal off-set, and one case of lateral and longitudinal off-set. Fig. 16 is a result of the 10th landing trial, where the release point is laterally off-setted about 190m from the center line. In the figure, the time histories of bank angle and lateral deviation are shown. The guidance to correct the lateral deviation started after the path capture phase in which the guidance command is wing level. The time histories illustrate that the simulation and flight are very close to each other, which means that the lateral-directional control response is sufficiently quick as it is designed. Flight tests of longitudinally off-setting the release point were also conducted, although the flight from the release to the path capture had already demonstrated the longitudinal control performance.

### 5.5 Closed-loop system response to M-sequence intentional disturbance

Intentional disturbance input of M-sequence to the control surface's command was prepared in order to identify the aerodynamic characteristics of the vehicle. Quality verification of the aerodynamic data estimated from wind tunnel tests is one of the ALFLEX program's goal. The landing flight test proved the quality of the aerodynamics prediction for longitudinal motion. Since the identified aerodynamic derivatives' differences were within the prediction, as a matter of course, the control system by using the data is stable with sufficient margin. On the other hand, concerning the lateral-directional motion, the maneuver oscillated by the aileron and rudder disturbances are not enough to identify the aerodynamic characteristics accurately. 11),12)

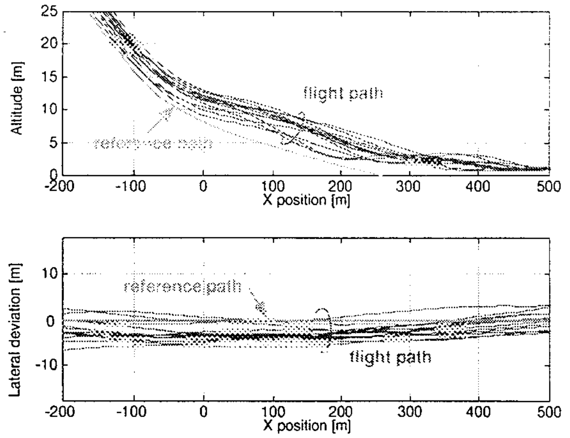

**Fig. 15 Flight trajectories before touch down**

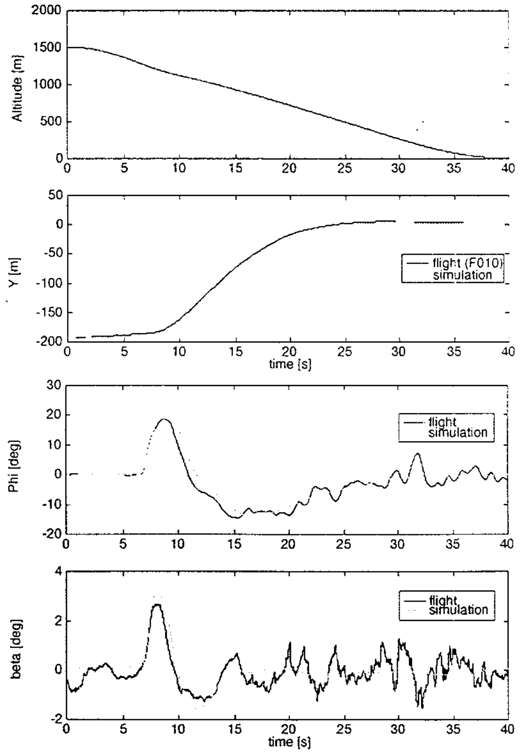

**Fig. 16 Flight trajectories, lateral off-set release**

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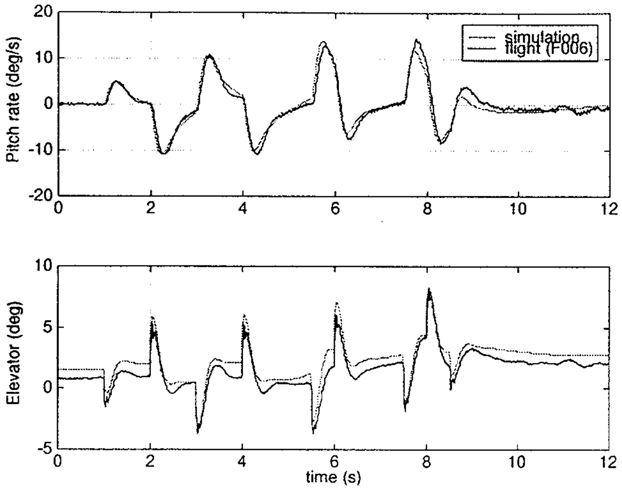

Fig. 17 Response to M-sequence disturbance

Fig. 17 shows the response of flight test and simulation from an intentional disturbance test landing flight. Although the shape of disturbance input is a step, the disturbance added on the control surface command is quickly suppressed by the feedback control. Time histories demonstrate the flight control system's stability and performance.

## 6. CONCLUDING REMARKS

The ALFLEX program completed all the planned landing flight trials successfully thanks to robustness of hardwares and appropriate design. It could demonstrate the technology readiness of the automatic horizontal landing for the future unmanned reentry space vehicles. The Japanese technology development scenario for a future space vehicle has stepped up to the next flight experiment program, HOPE-X, where the design results in the ALFLEX vehicle will be fully utilized. Through the development and fligh testing of the ALFLEX program, we could verify the approach for the design and development, and we experienced various kinds of lessons learned, which will be useful in the HOPE-X development under way.

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