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Evaluation of Guidance and Control Systems of a Balloon-Launched Drop-Test Vehicle

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Introduction

THE Japan Aerospace Exploration Agency (JAXA) has been researching key technologies for future space transportation. A series of flight experiments have been carried out to develop technologies for the planned H-II orbiting plane experimental (HOPE-X) [1] unmanned winged reentry vehicle: the orbital reentry experiment (OREX) [2], the hypersonic flight experiment (HYFLEX) [3], and the automatic landing flight experiment (ALFLEX) [4]. Following on from these earlier experiments, the two-phase high-speed flight demonstrator (HSFD) program was planned and implemented [5]. HSFD phase I aimed to inspect the environmental conditions at the designated HOPE-X landing site, whereas HSFD phase II (HSFD-II) was a drop test of an unpowered HOPE-X scale model to obtain transonic aerodynamic data on the vehicle's configuration.

After an investigation of alternatives, release from a high-altitude stratospheric balloon was selected as the launch method for HSFD-II [6]. This presented a couple of challenges. First, the experimental method is quite unique (as far as we are aware there have been only two similar previous experiments) and so there was a lack of experience and knowledge on which to build. At the same time, this type of experiment has a similar drawback to the testing of space systems; that is, incremental testing and flight envelope expansion, which are normal in the development of airplanes, are impossible: the vehicle must be able to fly the full mission from its very first flight. Accordingly, it is important to exhaustively evaluate the guidance and control (G&C) systems by computer simulation beforehand.

Recently, a balloon launch has been considered to have great potential as a low-cost launch method for flight experiments [7–9]. This Note describes a method for evaluating the G&C systems of strongly nonlinear systems, such as a balloon-launched drop-test vehicle. It was iteratively used in the design and evaluation process to tune the theoretically designed G&C systems [10] using a statistical method [11]. This iteration was the key to establish the flight safety.

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Overview of High-Speed Flight Demonstrator Phase II

Generally, in balloon-launched flight experiments it is impossible to control the horizontal position of release, which results in great difficulty for the flight safety evaluation and complicates vehicle recovery. In the case of HSFD-II, the vehicle is unpowered, and being optimized for hypersonic reentry flight, its subsonic glide characteristics are poor, severely limiting its gliding range performance. To overcome these problems, multiple recovery sites were prepared in the flight test area, and it was required that the vehicle be able to glide to at least one of these sites regardless of where it was released within the experimental area. Consequently, there is no nominal trajectory for this experiment.

The HSFD-II flight consists of six phases as shown in Fig. 1. After the release from the balloon, the vehicle maintains a pitch angle of -80 deg (a -90 deg flight-path angle) and descends in an acceleration phase to accelerate towards the target Mach number set for the experiment. Approaching the target Mach number, the vehicle pitches up in a trajectory insertion phase, and then enters a Mach number hold phase during which aerodynamic data are acquired. After data acquisition is complete, a return phase is initiated in which the vehicle flies along a heading alignment cylinder (HAC) to orientate its flight path towards a recovery site. The final phase is a recovery phase, during which the recovery procedure operates sequentially. This final phase is not within the scope of this Note.

Guidance and Control Systems

There were two main challenges in designing the G&C systems of this vehicle: there is no nominal trajectory because it is impossible to control the horizontal release position, and the vehicle is not controllable for a short time after separating from the balloon because of low dynamic pressure.

Because the HSFD-II's G&C systems are described fully in [10], only a brief outline is given here. The G&C law has two fundamental requirements: precise tracking of the target Mach number during data acquisition, and the selection of a suitable recovery point and precise guidance to that point.

The G&C systems switch between guidance laws according to the flight phase. At the beginning of the return phase, the guidance law calculates the vehicle's downrange at a constant flight-path angle, and selects the most suitable recovery point. Then it determines the position of a constant-radius HAC such that the downrange matches the distance from the present position to the recovery point flying via the HAC.

The control laws were designed by the multiple-delay-model and multiple-design-point (MDM/MDP) method [12]. The vehicle's velocity ranges from zero to supersonic, and dynamic pressure also varies greatly during the flight, giving a very large flight envelope. The control gains were therefore designed by dividing the flight conditions into three regions, and dynamic pressure compensation and gain scheduling were applied.

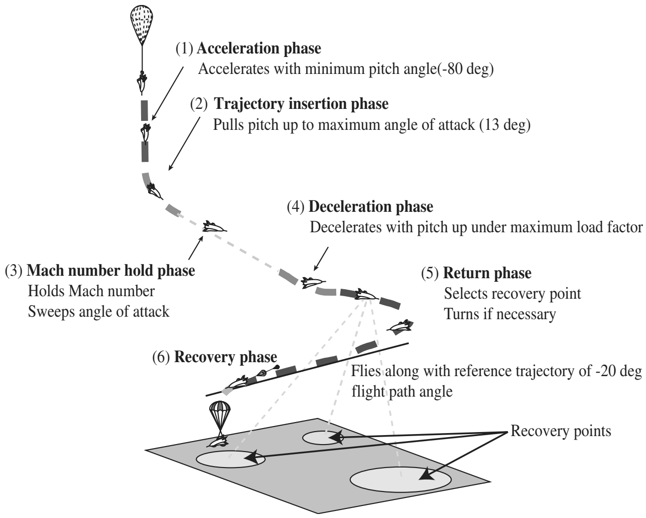

Fig. 1 Mission sequence.

The G&C systems were then evaluated and their parameters were adjusted if they failed to satisfy the design requirements. First, control gains were tuned to cancel the effects of influential parameters. If the G&C systems still had poor performance after this, then guidance gains were also tuned. If no feasible gains could be achieved even after this process, it would be necessary to reconsider other parameters such as the design of the flight phases, the number of recovery points, the vehicle's structure, and so on.

Evaluation Method

We applied three approaches to evaluate the G&C systems: linear analysis, sensitivity analysis, and Monte Carlo simulation (MCS). Because there is no nominal trajectory, evaluation purely by linear analysis or sensitivity analysis, which were used in earlier experiment programs [4,13], would have been inadequate, and so MCS was used as the principal evaluation method.

The vehicle was modeled with 144 errors, all of which were incorporated in each simulation. These consisted of vehicle model errors, aerodynamic model errors, actuator model errors, sensor model errors, environmental model errors, and separate condition errors. Measured errors, such as mass of the vehicle, were modeled with uniform distributions, whereas estimation errors, such as aerodynamic coefficients, were modeled with normal distributions. The target Mach numbers for the tests were set at 1.2, 1.05, and 0.8, and the G&C systems were evaluated at each target Mach number.

Mission success was judged according to criteria for six failure modes: divergence, recovery failure, excessive equivalent air speed (EAS), maximum dynamic pressure, maximum and minimum load factors, and insufficient data acquisition. Because our aerodynamic model was limited with respect to angle of attack (AoA) data in the range -10–$+30$ deg, simulation results would be less reliable under excessive AoA conditions, and this was judged to be a divergence case. The recovery failure and excessive EAS conditions were defined from the viewpoint of safe parachute use, with a maximum parachute deployment EAS limit of 103 m/s. Dynamic pressure and load factor limits were set at 15.68 kPa and -1.0–$+3.5$ g respectively. During the Mach number hold phase, it was required that the target Mach number be maintained within ± 0.03 Mach and that AoA sweep from 10 to 2.5 deg at less than 2 deg/s. Failure to satisfy these conditions was judged as an insufficient data acquisition case.

Our goal was to reduce the probability of catastrophic failure (a failure that might result in the vehicle's destruction) to less than 0.3%, which corresponds to the 3σ (standard deviation) value. The G&C systems were refined iteratively; if they had poor performance, design and evaluation were repeated until the goal was met. Each failure case in the MCS results (that is, MCS simulation cases which failed to meet the criteria) was investigated in detail to clarify the cause of the failure. For instance, in the case of a recovery failure, the trajectory was examined to determine the possible causes, such as insufficient directional guidance or control gains, or unsteady oscillation during the Mach number hold phase.

Failure cases were also closely examined by a statistical method [11] that itself uses MCS as an essential tool to determine which error source, or combination of error sources, are most influential on the failure. In this method, MCS is conducted incorporating the 144 aforementioned errors, using new error sets that are derived from the error sets of failure cases. A new error set is derived from a failure case error set by randomly setting each element to either the value from original error set or zero. This procedure is repeated to generate many new error sets, and the results of MCS with these error sets are statistically processed to extract the influential error sources.

These information were fed back to the G&C design, and the gains were tuned to cancel the failures. This procedure was repeated until capable G&C gains were obtained.

Monte Carlo Simulation

In MCS, a large number of simulations are carried out with different combinations of random error for all error sources. One thousand simulation cases were carried out for each target Mach number and the results were examined. When the level of significance was set at 5%, the upper limit of confidence interval was 0.77% for three failures out of 1000 runs, and this risk was accepted by the project management.

The results of MCS are shown in Table 1. The requirements in Table 1 are listed in order of decreasing priority. If a simulation result violates more than one requirement, it is counted only as violating the highest priority requirement.

All failure cases were investigated in detail. For example, looking at the cases of load factor violation, load factor exceeded 5.6 g in three out of 13 failure cases, whereas the maximum load factor requirement was 3.5 g. In these cases, the vehicle showed large rolling oscillations at the end of the Mach number hold phase, when AoA was very low. The vehicle continued to pitch up to decelerate while undergoing these unsteady rolling motions, which resulted in an excessive load factor that might cause serious structural damage. To reduce the risk, four failure cases for Mach 1.2 were investigated by the statistical method in [11], which identified one of the products of inertia as the dominantly influential error source on this unsteady rolling motion. Both the G&C systems and the vehicle model were investigated, but it turned out that it was difficult to reduce this failure without additional structural vibration tests. However, this additional test was not implemented because the probability of catastrophic failure due to this factor was regarded as being acceptably low.

Some types of failure can be avoided by applying suitable flight operation procedures. For example, if there is a strong steady wind, vehicle release can be delayed until it abates. So long as simulations show that flights under moderate wind conditions will succeed, this type of failure can be neglected by imposing a flight restriction. Consequently, flexibility in the drop timing is an effective way of avoiding some types of failure.

Considering flight operation procedures, the results of the MCS evaluation of mission success probability are summarized as follows: Four cases of recovery failure can be avoided by appropriate flight

Table 1 Results of MCS (number of failure cases out of 1000 runs for each Mach number)

	Mach number			
Required specification	1.20	1.05	0.80	Total
Divergence	0	0	0	0
Recovery failure	2	1	1	4
Excessive EAS	9	10	5	24
Maximum dynamic pressure	0	0	0	0
Maximum and minimum load factors	4	2	7	13
Insufficient data acquisition	0	1	1	2
Total	15	14	14	43

operation procedures or restrictions. Twenty-four cases of excessive EAS are very slight violations, and it was judged that the risk of loss of vehicle in these cases was acceptably low. There are 13 cases of load factor exceedences. Three of these cases for a Mach 1.2 target are very serious exceedences that might result in vehicle destruction. The evaluated probability of mission failure is 43/3000, and that of possible vehicle damage is 3/3000, which is less than the requirement of 0.3% for the catastrophic failure. This evaluation indicates that the G&C systems have adequate performance.

Flight Results

The first flight experiment was carried out on 1 July 2003 at the Esrange test site in Sweden, with a target Mach number of 0.8. During the flight, global positioning system (GPS) signals were lost from during the vehicle's ascent under the balloon until the end of the flight, and so the vehicle had to rely on onboard inertial navigation.

The flight data showed the following: Mach number was maintained at 0.8 ± 0.03, angle of attack swept from 10.0 to 2.5 deg at a rate of less than 2.0 deg/s. Maximum dynamic pressure and maximum and minimum load factor were 9.57 kPa, $+2.24$ g, and zero, respectively. The point of the parachute deployment under onboard navigation was within the recovery cone determined by the parachute envelope, and altitude and position errors were 11.0 and 29.8 m, respectively. EAS at the recovery point was 92.7 m/s. These results show that all criteria were satisfied.

Unfortunately, there was malfunction in the recovery system which made it impossible to continue the flight test campaign. If possible, it would be desirable to repeat the experiment. This would enable the G&C systems to be evaluated by repeated flights and the simulation model parameters, such as the aerodynamic model, to be revised. However, from the results of the first flight test, we confirmed the following [14]. The G&C systems worked properly as designed, even though navigation performance was degraded by loss of GPS positioning. After the flight, a Monte Carlo simulation was carried out using the mass properties, atmospheric data, and steady wind measured on the day of the flight. The simulation result was generally similar to the actual flight-test data, except for the vehicle motions just after separation, when dynamic pressure was low.

Conclusions

In this Note, we have discussed the method used to evaluate the guidance and control (G&C) systems of high-speed flight demonstrator phase II. Monte Carlo simulation played a principal role and was also used for tuning the G&C gains by identifying influential parameters in failure cases. Flight test results confirmed that the G&C systems performed the required mission appropriately, and postflight analysis showed that the systems worked as designed. From these facts, we conclude that our evaluation method is of practical use.

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