On the Automatic Landing FLight EXperiment (ALFLEX)

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ABSTRACT

The National Aerospace Laboratory (NAL) and the National Space Development Agency of Japan (NASDA) have been cooperating to research the unmanned H-II Orbiting PlanE (HOPE). In this research, the Japanese government required the Automatic Landing FLight EXperiment (ALFLEX) with a HOPE scale model as an essential step in the development of HOPE. The purpose of the ALFLEX project was to demonstrate the fundamental technology for the HOPE automatic landing. We conducted flight experiments at Woomera in South Australia from June to August, 1996. This paper summarizes the ALFLEX project.

1. Introduction

NAL and NASDA are jointly researching HOPE which is a Japanese original unmanned reusable space transportation system and which facilitates various space activities. To demonstrate automatic landing technology for HOPE, we planned ALFLEX project which was authorized by Japanese government in 1993. We designed, manufactured, and tested the experiment system in Japan and performed a series of operations including facility installation, ground tests, hanging flight tests and automatic landing flight experiments at Woomera airfield in South Australia of the Commonwealth of Australia from March to August 1996. All 13 flight experiments were successful and the automatic landing system of the ALFLEX was proven to be appropriate. In addition, we obtained flight data concerning guidance, navigation and control and aerodynamic characteristics as we expected.

2. Objectives

The Objective of ALFLEX was to demonstrate the fundamental technology for HOPE automatic landing using a scale model which has an outline similar to that of HOPE.

The HOPE automatic landing has four major technically difficult characteristics. Two of them are "pilotless" and "thrustless". Therefore, we cannot rely on the human adaptability to changes of flight conditions as we can in piloted flight. Furthermore HOPE must land with just one approach since the absence of thrust prevents go-around. This means that the design of the system must be reliable. The other two technically difficult characteristics are the low lift-drag ratio and the aerodynamic instability which originate in the aerodynamic requirements of vehicles designed for hypersonic flight. The low lift-drag ratio makes the approach path angle large and the approach velocity large. The aerodynamic instability of pitch and yaw attitude make the vehicle unstable without active control of the control surfaces. In this manner the development of the HOPE automatic landing system raises technically difficult questions not usually encountered with aircraft.

To address such difficulties, the establishment of the automatic landing system design is important and its validity must be demonstrated in flight experiments. In the ALFLEX project, therefore, the guidance, navigation and control design method was established and its validity was evaluated as a prerequisite for HOPE. In addition, technical data necessary for the development of the HOPE automatic landing system was obtained and the flight experiment technology with a scale model was also established. In summary, the objectives can be itemized as follows.

(1) to establish and demonstrate automatic landing system technology
- to establish and evaluate the design method of guidance and control
- to demonstrate and evaluate the navigation method

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(2) to obtain low-speed flight characteristics
- to obtain flight characteristic data
- to obtain ground effect data

(3) to establish flight experiment technology with a scale model
- to establish experiment and analysis method

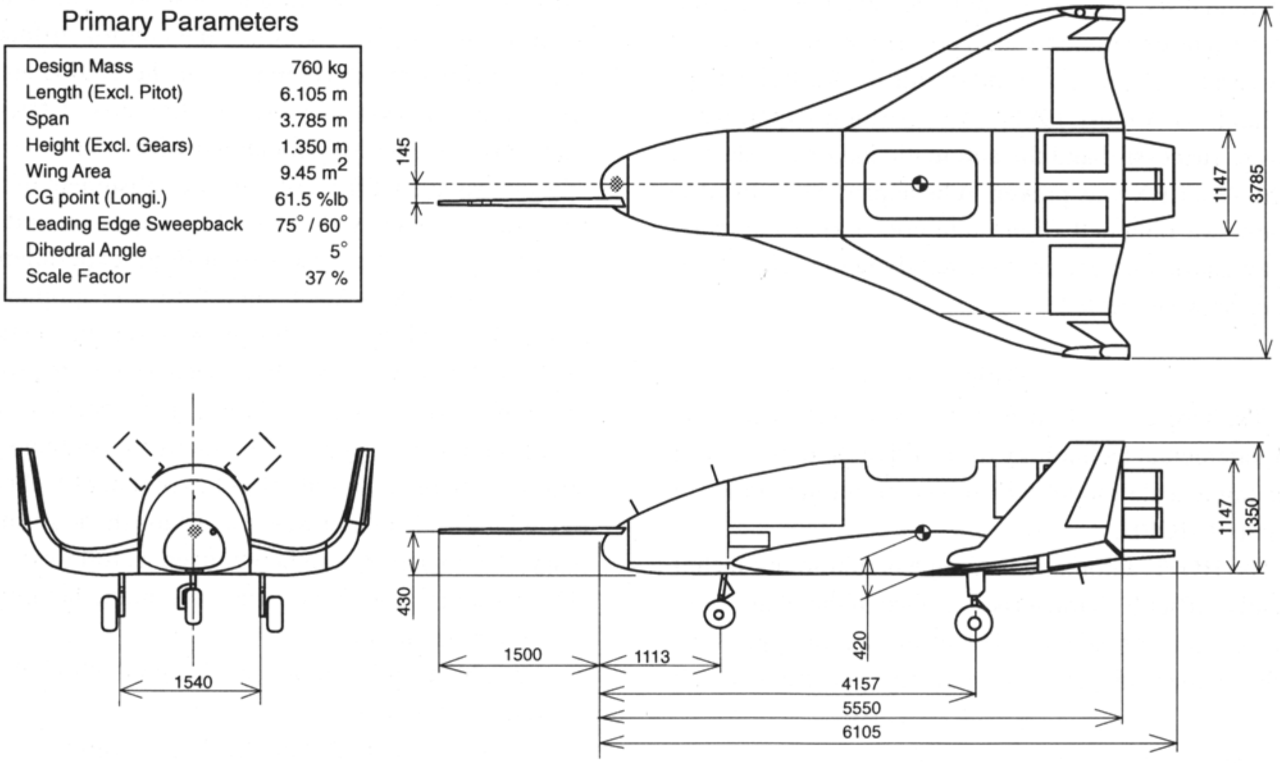
3. System Design

The outline of the vehicle is called HOPE04c designed for HOPE itself in 1992 (Heisei 4 in the Japanese calendar) by Fuji Heavy Industry, Ltd. The runway length was supposed to be 1000m to facilitate the selection of runways. The scale ratio derived from these is 37%. Major design changes from HOPE04c are the hole on the upper surface of the body for hooking the cable which is used to hang the vehicle at its center of gravity from the mother helicopter and the fixed landing gear in addition to a long Pitot boom. The outline of the vehicle is show in Fig. 1.

The method used to hang and separate the vehicle in the sky is called the gimbal hanging method. The vehicle is supported with one cable hooked to the gimbal at the center of gravity of the vehicle. With this method, the vehicle can move in 5 degrees of freedom, i.e., 3 attitude movement and 2 parallel movement. Its advantage compared to conventional hanging methods, is that the onboard control system can be operated even in the hanging mode. In other words, we have the following benefits.
- the health check of the flight control system before separation
- the active attitude stabilization by the onboard control system just before the separation to separate smoothly
- the vehicle aerodynamic data acquisition without separation using the tension of the cable

The navigation system in the automatic landing flight phase after the separation consists of Inertial Measurement Unit (IMU), Microwave Landing System (MLS) and Radio Altimeter (RA). In the hanging flight phase, however, the Differential GPS (DGPS) is also used to improve the navigation accuracy before separation. Major topics of the control system are side slip angle control with Air Data System (ADS) and the crab touch-down method by which the vehicle directs its nose windward against the side wind.

In the flight path design, the wind model was simi-



Primary Parameters

Design Mass	760 kg
Length (Excl. Pitot)	6.105 m
Span	3.785 m
Height (Excl. Gears)	1.350 m
Wing Area	9.45 m^2
CG point (Longi.)	61.5 %lb
Leading Edge Sweepback	75° / 60°
Dihedral Angle	5°
Scale Factor	37 %

Fig. 1 Three-way Projections of ALFLEX

larly scaled down to 37% from that of HOPE. The flight path itself is also similar to that of HOPE. The nominal flight path is shown in Fig. 2.

The nominal flight path consists of 5 phases.

- path capture phase
  accelerate and capture the equilibrium glide path
- equilibrium gliding phase
  fly at a constant speed and constant path angle
- preflare phase
  reduce vertical speed at the rate of 0.5G
- shallow glide slope phase
  fly at a constant path angle of 1.5 degrees
- final flare phase
  reduce the vertical speed to 0
- ground roll phase
  reduce the speed to 0

The capture phase is special to ALFLEX and not included in the HOPE approach and landing phase.

The sequence of the experiment is as follows. First the mother helicopter hangs the vehicle attached to the hanging equipment (combined configuration), ascends to an altitude 1500 m and accelerates to a speed of 90Kt (about 46m/s). Next, the hanging equipment pays out the cable to make the vehicle fly in the 5 degree-of-freedom configuration after the vehicle control system power-on. Finally, the mother helicopter flies horizontally towards the runway at a speed of 90Kt and release the vehicle at a point 2700m from the runway. The separated vehicle flies along the pre-determined nominal flight path, approaches the runway and touches down. After touchdown it controls ground roll with the steering system of the nose landing gear, reduces speed with the dragchute and the braking system of the main landing gear and stops. The sequence and the hanging flight configuration are show in Figs. 3 and 4, respectively.

4. Experiment System

The experiment system consists of the vehicle, the mother helicopter system and the ground equipment. The mother helicopter system consists of the mother helicopter itself which flies with the vehicle hung, the mother helicopter onboard equipment which changes the flight mode of the vehicle and performs the separation operation etc. and the Hanging Equipment. The ground equipment consists of the flight control system which monitors the system status of the flying vehicle and controls the experiment sequence, the navigation ground system (ground stations of MLS and DGPS), the laser tracker and the tracking radar which measure the flight position of the vehicle on the ground.

Flight data of the vehicle is sent by the telemetry system to the ground. It is displayed on the flight control desk together with the data of the laser tracker and the tracking radar. The flight control equipment are installed in the flight control facility. A schematic diagram and conceptual drawing of the experiment

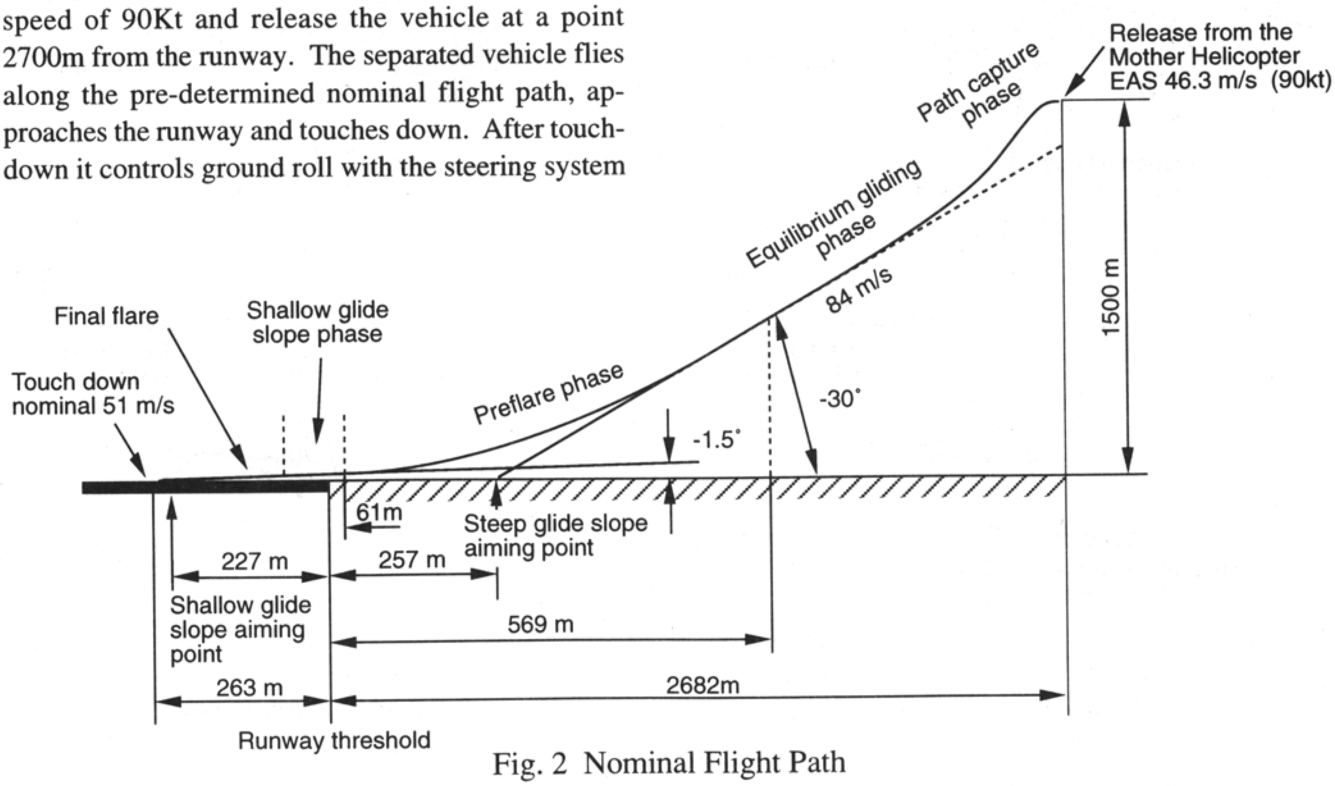


Fig. 2 Nominal Flight Path

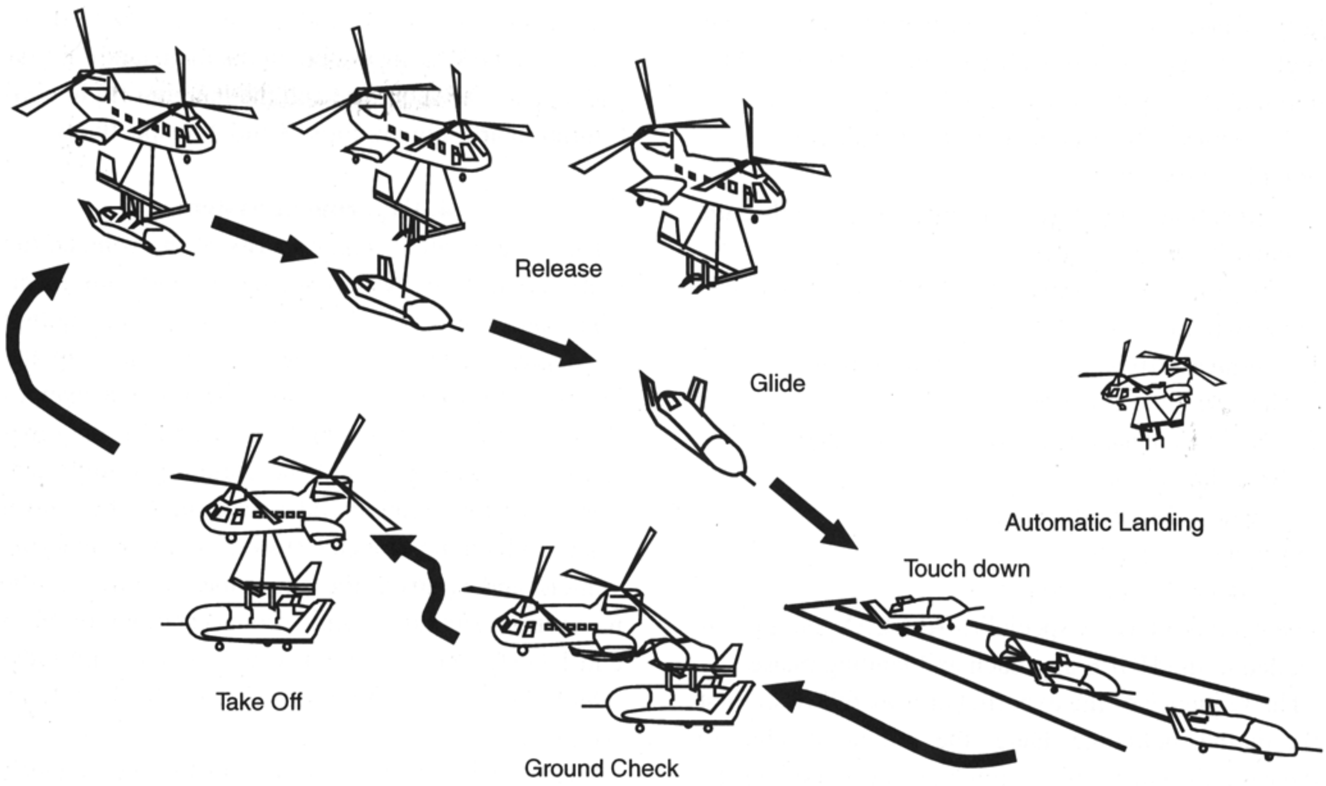


Fig. 3 Sequence of Automatic Landing Flight Experiment

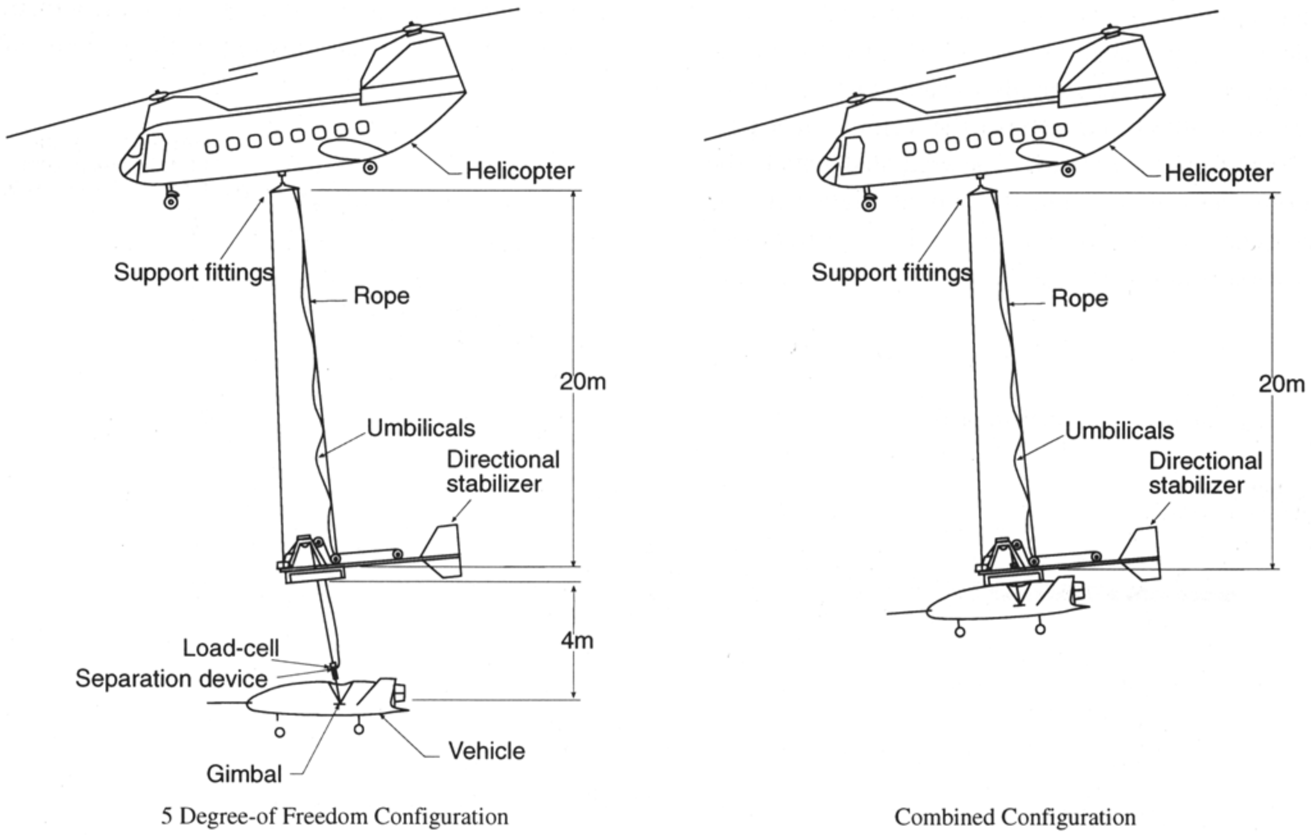


Fig. 4 Hanging Flight

system are shown in Figs. 5 and 6, respectively.

The automatic landing experiment was done in Woomera, the Commonwealth of Australia. Location of Woomera is shown in Fig. 7.

5. Preliminary tests

The functions of the experiment system were checked on the ground and the same functions were checked again in flight with the vehicle hung by the mother helicopter as the preliminary operations before the automatic landing flight experiment.

All the system were tested including MLS which had not been used in the domestic hanging flight test.

(1) Ground Tests

The following ground tests were performed.

- Vehicle System Test

  Health check after the transportation was performed on the ground.
- Ground Equipment System Test

  Integrated functions and performances of the ground equipment were checked after installation.
- Vehicle/Ground Equipment Interface Test

  Functions and Performances were checked with the vehicle and the ground equipment connected.
- Ground-Roll functions confirmation test

  Functions related to the ground-roll were checked. 5 ground-rolls were performed with the vehicle driven by a car from 26 April to 4 May, 1996 in Woomera.
- Vehicle/Mother Helicopter System/Ground Equipment Interface Test

  Functions and performances were checked with the vehicle, the mother helicopter system and the ground equipments integrated.

(2) Hanging Flight Tests

The following items were performed.

- Integrated functions confirmation

  Integrated functions of all the equipment were confirmed with the combined hanging configuration during the level flight of the mother helicopter. In addition, the accuracy of the navigation system with the signals of GPS, MLS, RA etc. was also checked.
- Control System performance evaluation

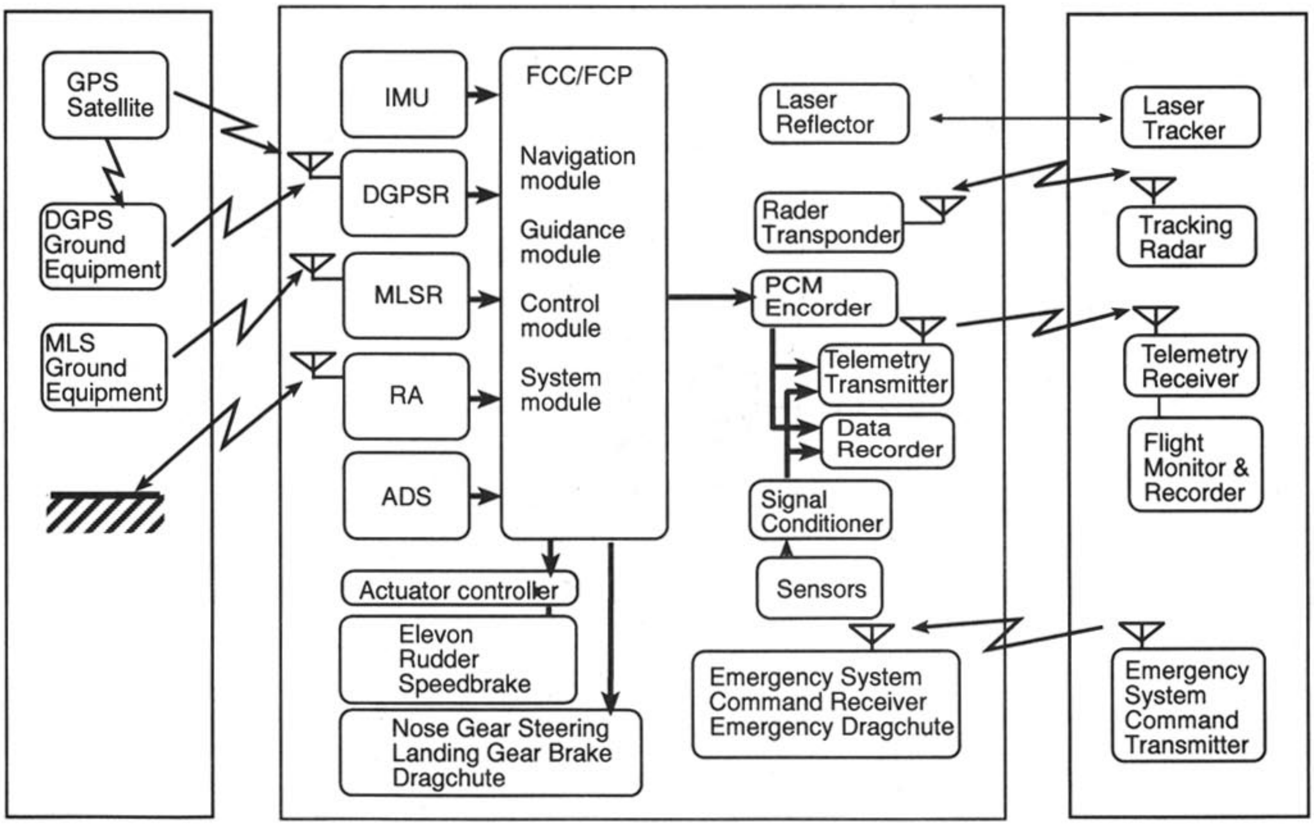


Fig. 5 Schematic Diagram of Experiment System

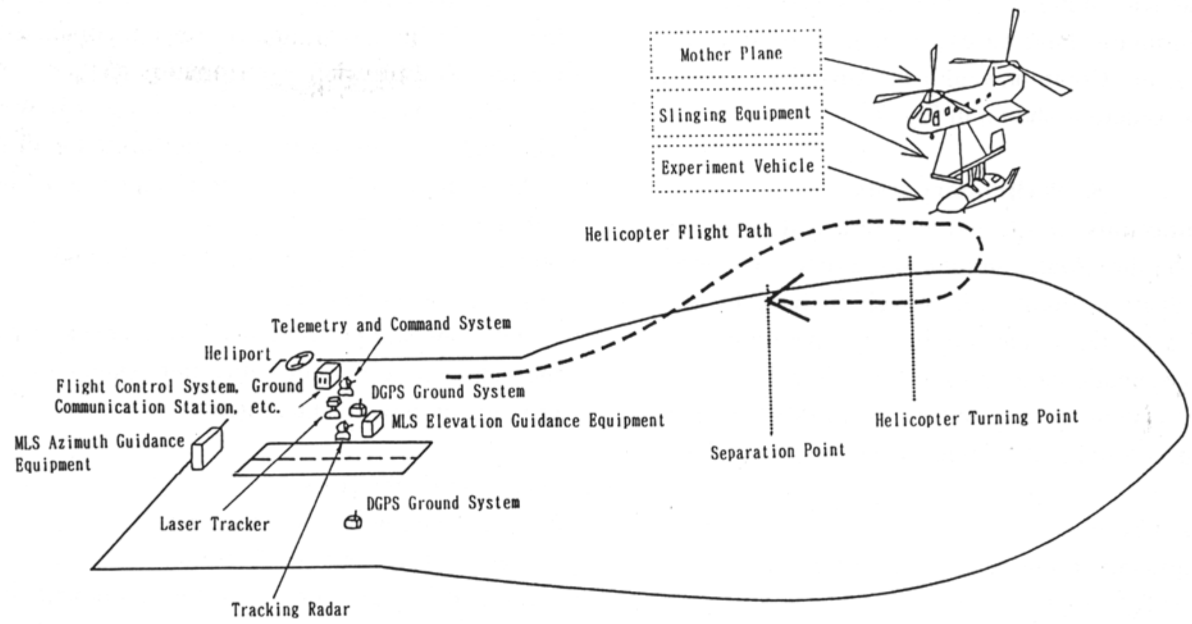


Fig. 6 Conceptual Drawing of Experimental System

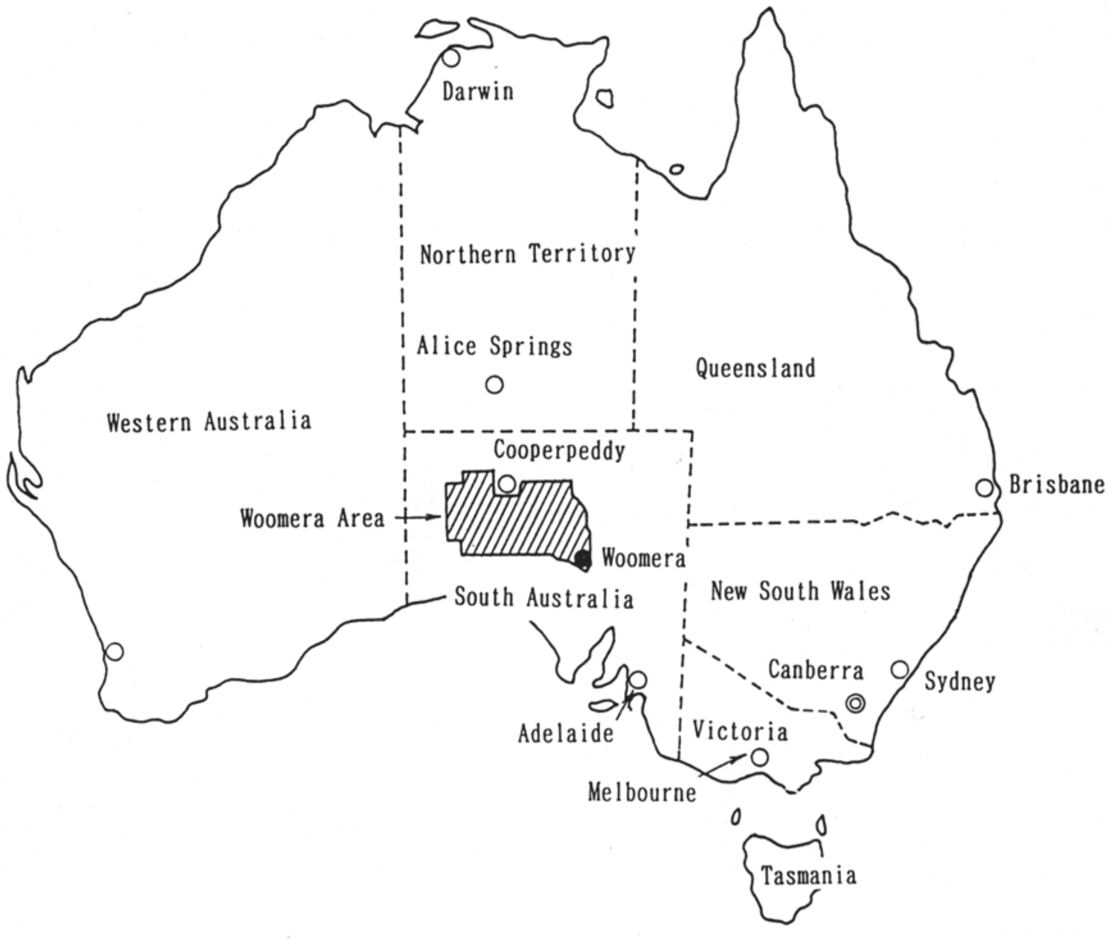


Fig. 7 Woomera Airfield

It was confirmed that the vehicle is stably controlled as designed in the 5 degree-of freedom configuration as the hanging cable is gradually payed out after the control system power-on.

- Flight Characteristics evaluation

  The aerodynamic characteristics of the vehicle were evaluated with the data measured when several command signals to the control system change the attitude of the vehicle in the 5 degree-of-freedom configuration.

The hanging flight tests before the automatic landing flight experiment were conducted from 21 May to 25 June and the items above were confirmed.

6. Automatic Landing Flight Experiment

Two kinds of flight experiments were performed. One demonstrates the validity of the design, especially guidance/navigation/control design and the other is data acquisition about the guidance/navigation/control performances and flight characteristics. The flight experiments are summarized as follows.

(1) Design Validation with Nominal Flight

- Flight along the nominal flight path with the separation at the nominal point
- Wind condition less than 60% of the design wind

(2) Data Acquisition with Off-nominal Flight

- Offset separation by the shift of the separation point from the nominal one
- Wind condition relaxation to 100% of the design wind
- Flight performance evaluation with the attitude movement due to the vibratory operations of the control surfaces

The first flight experiment was successful on 6 July. The flight path after the separation and the movement after touch-down was satisfactory within the precalculated range. Pictures of the flying vehicle are shown in Fig. 8.

The second flight experiment was almost the same. Since both trials proved the validity of the design, the data acquisition with off-nominal flight started from the third flight. 13 flight experiments were performed from 6 July to 15 August and the data was also obtained as planned.

7. Development schedule and structure

In 1993 we initiated a joint design team among NAL/NASDA, Kawasaki Heavy Industry Ltd., Fuji Heavy Industry Ltd. and Mitsubishi Heavy Industry Ltd. to promote the preliminary and critical design. It took about 2 years to manufacture the vehicle, the mother helicopter system and the ground equipment.

Ground roll tests were conducted at Utsunomiya airport in August, 1995 and all the systems except MLS were checked in the domestic hanging flight tests at Nagoya port from October to January, 1996. The experiment system was then transported to Australia.

In Woomera, construction works started November, 1995. The vehicle was assembled and the ground equipment were installed in March, 1996. From April to June, the preliminary tests are performed and from July to August automatic landing experiments were executed. The schedule is shown in Fig. 9.

A total of about 80 members including the NAL/NASDA experiment team (about 30 members) and engineers of manufacturers participated in ALFLEX.

ALFLEX was also a cooperative project between Japan and Australia under the agreement between NASDA and Australia. The Australian Space Office was the representative organization and integrated various supports from Deportment of Defense, Defense Centre Adelaide, Defense Support Centre Woomera (who controls Woomera airfield), Civil Aviation Authority, Spectrum Management Agency, Bureau of Meteorology etc. In addition, Australia assigned the Safety Operations and Liaison Officer who arranged practical affairs at Woomera between both. Cooperating organizations of Japan and Australia are shown in Fig. 10.

8. Summary

The ALFLEX project was a development of automatic landing technology which involves technical difficulties such as no thrust, no pilot and HOPE outline unsuitable for low-speed flight and which is the first challenge of automatic landing in Japan.

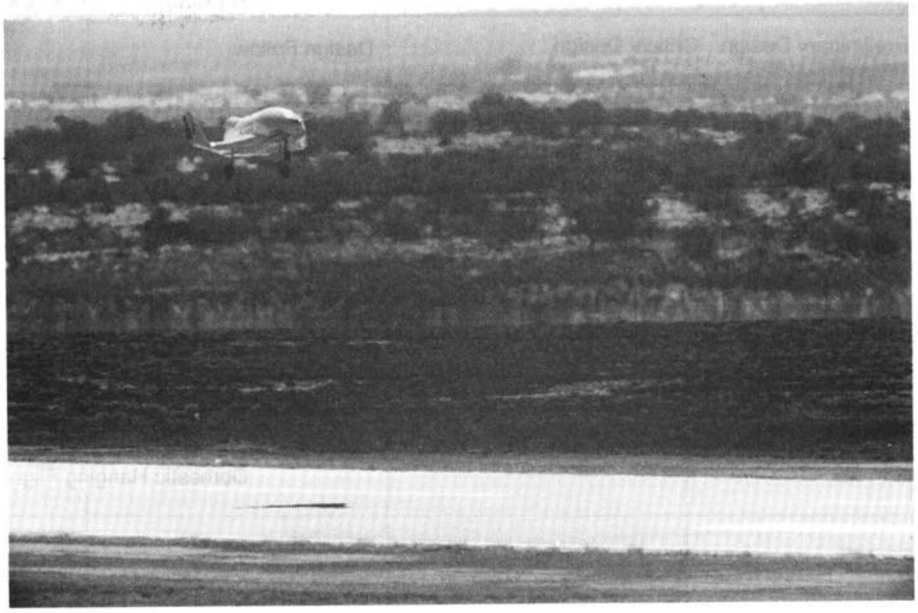
Cooperation of NAL/NASDA, manufacturers, Australian government and related organizations was the cause of 13 successful experiments which gave us the prospect of the HOPE automatic landing system development.

We sincerely appreciate those who support the ALFLEX project.

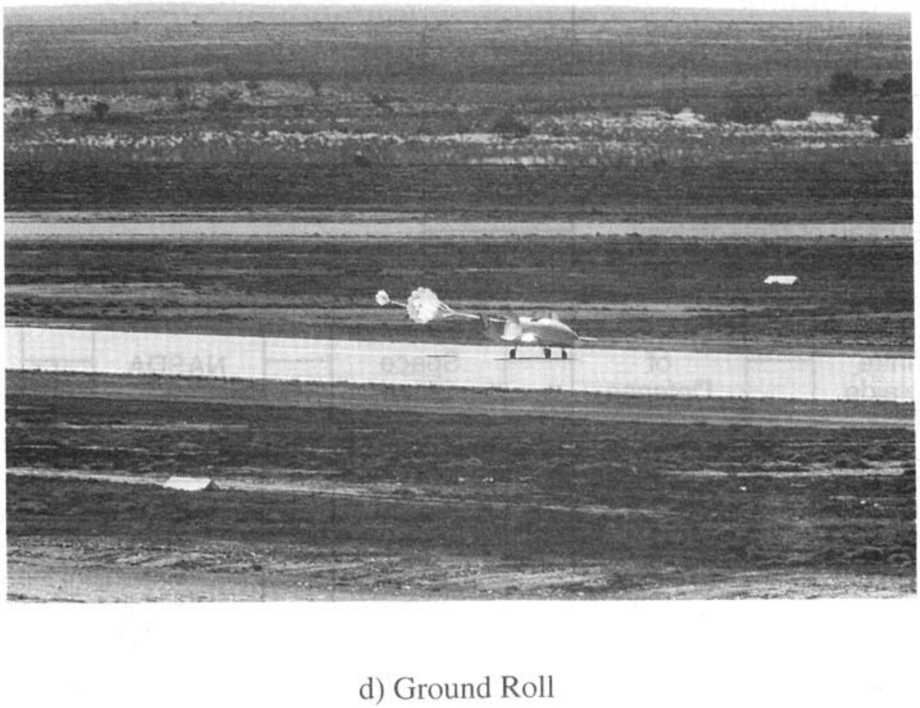
a) Release

b) Equilibrium Gliding Flight

Fig. 8 Pictures of ALFLEX Vehicle during the Automatic Landing Flight



c) Flare



d) Ground Roll

Fig. 8 continued

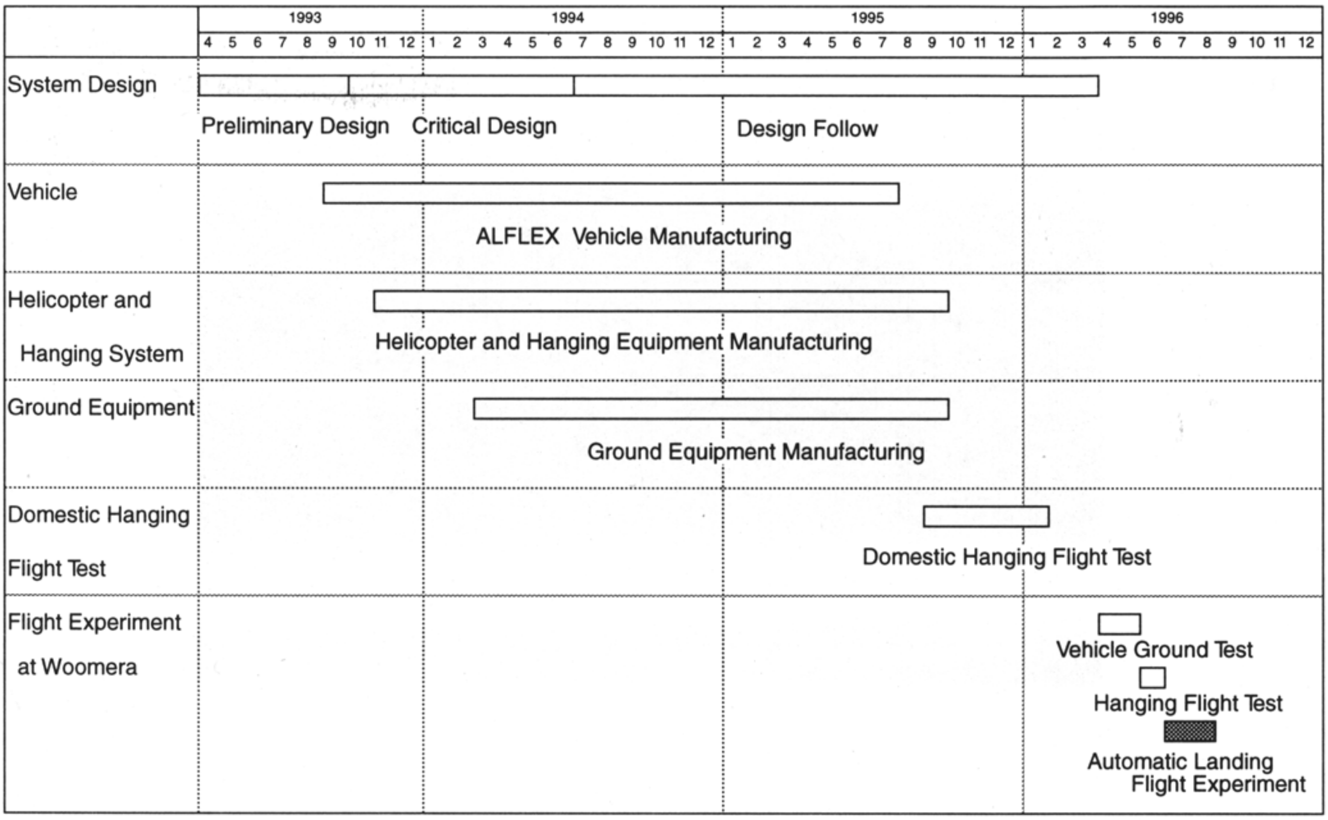


Fig. 9 ALFLEX Schedule

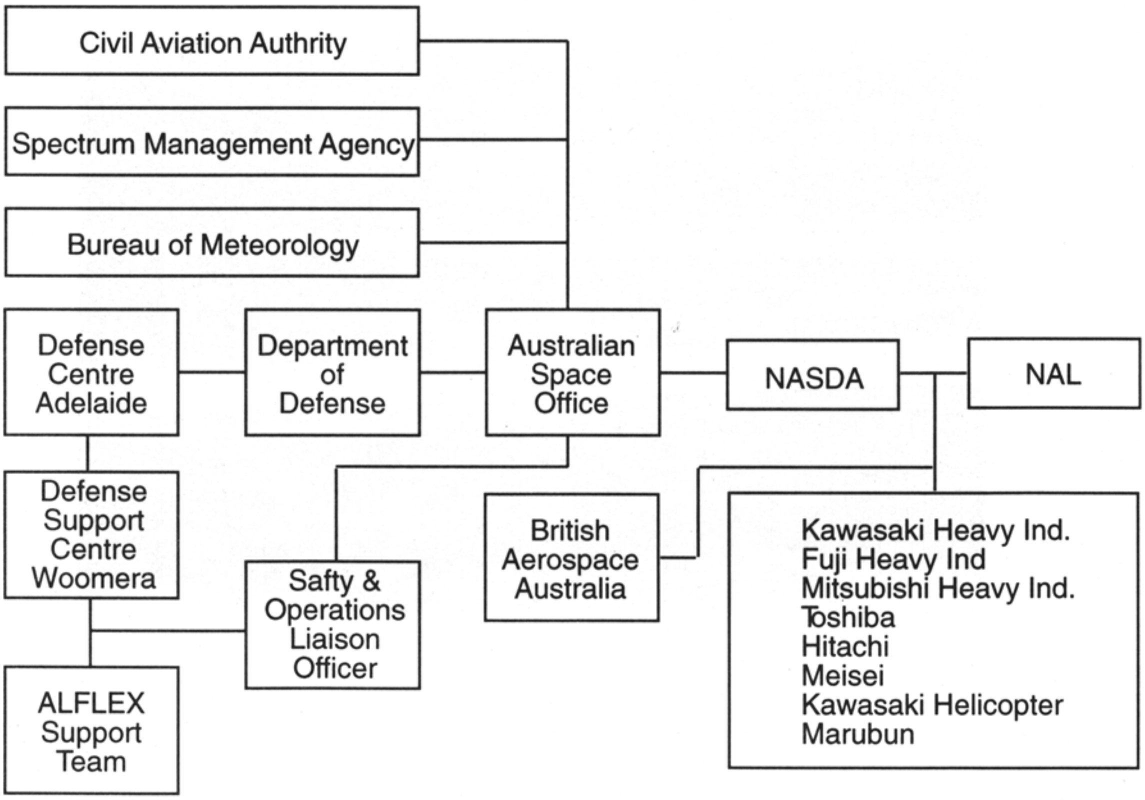


Fig. 10 Cooperating Organization for ALFLEX