FLIGHT PLAN AND FLIGHT TEST RESULTS OF EXPERIMENTAL SST VEHICLE NEXST-1

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Abstract

On October 10, 2005, a supersonic flight test as a major event of National Experimental Supersonic Transport (NEXST) project conducted by Japan Aerospace Exploration Agency (JAXA) was carried out successfully in the Woomera Test Range in South Australia. The non-powered airplane attached to the rocket booster was launched to an altitude of 19 kilometers, accelerated to a speed of Mach 2, twice the speed of sound. Separated from the booster, the airplane flew and acquired various technical data to verify the validity of the advanced aerodynamic design. It made a perfect automatic flight as designed and landed on the desert safely. In this paper, the outline of this flight test and some results are described.

1 Introduction

To establish advanced aerodynamic design technologies applicable to a next generation supersonic transporter (SST), National Experimental Supersonic Transport (NEXST) project [2][3] has been promoted by Japan Aerospace Exploration Agency (JAXA).

In this project, an experimental unmanned airplane named "NEXST-1" was developed under novel aerodynamic design concepts for a drag reduction such as a cranked arrow planform, a warped wing, an area-ruled fuselage, and a natural laminar flow wing design (figure 1). This airplane has a length of 11.5 m, a width of 4.7 m, and a weight of 1,900 kg, which is a size of 11 % of a future SST. Because external equipment except the wing and fuselage is undesirable to verify the validity of such design concepts, the airplane has no engine or any other thrust equipment. Alternatively, it is attached to the solid rocket booster, which takes the airplane to a desirable altitude and speed (figure 2).

This paper presents the plan of this flight test in order of the flight phases. Additionally some results of the actual flight test are also introduced briefly.

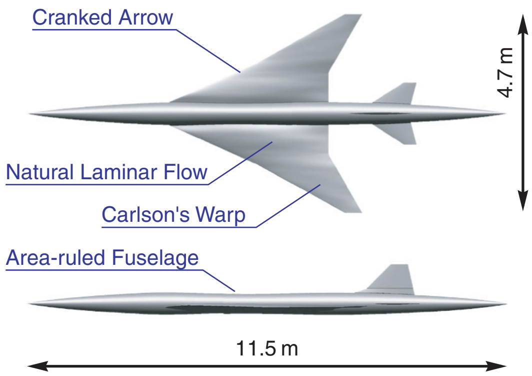

Fig. 1 Aerodynamic Design Concepts in NEXST-1

Fig. 2 NEXST-1/Booster Configuration

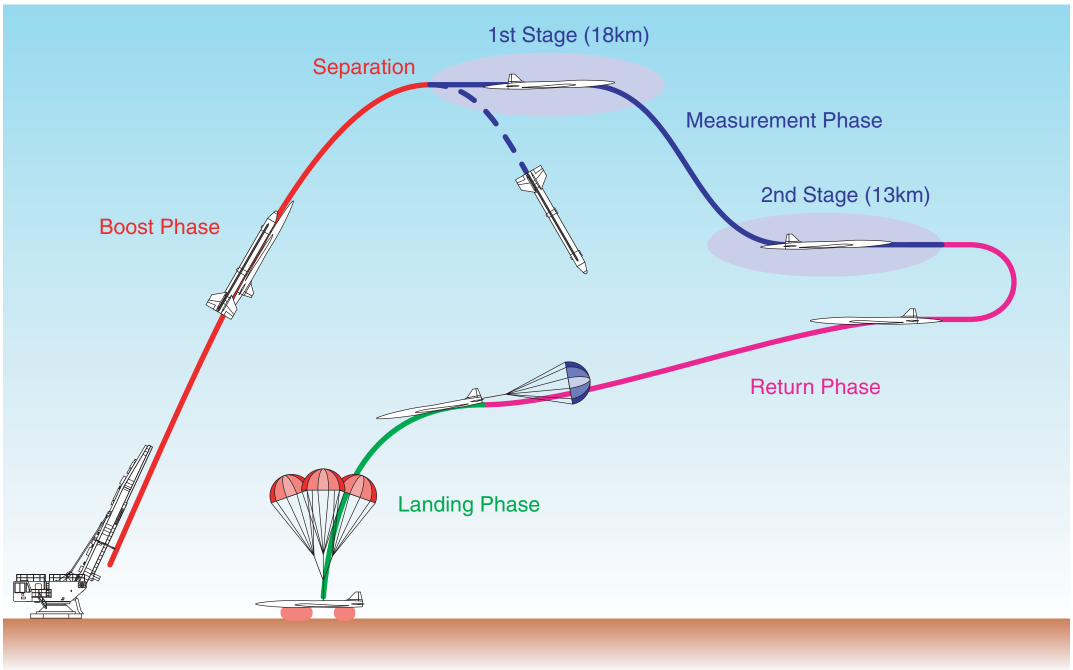

Fig. 3 Flight Test Sequence

2 Flight Plan

This flight test is performed in order of the sequence as follows; 1) Boost phase, 2) measurement phase, 3) return phase, and 4) landing phase (figure 3).

In the boost phase, the experimental airplane is launched by the solid rocket booster. The booster takes the airplane to an altitude of 19 km, and it separates from the airplane. While the airplane is attached to the booster, the airplane leaves the flight control to the booster.

The airplane starts the measurement phase after the separation, in which it acquires various technical data including flight characteristics and surface airflow conditions. The measurement phase consists of two stages altering a flight altitude, or Reynolds number. The first stage is performed at an altitude of around 18 km, while the second one around 13 km. The altitudes are restricted within the range from 10 km to 21 km subject to flight safety constraints.

In the return phase following the measurement phase, the airplane flies toward a landing area, which is a flat area located at 15 km west from the launch site.

Approaching the landing area, the airplane starts the landing phase, in which it deploys the parachutes sequentially and lands. The touchdown is cushioned by air bags.

The booster in the boost phase and the airplane after the separation fly autonomously under the preprogrammed guidance and control and do not receive any command from the ground station, except an emergency termination command.

Since the flight trajectory exceeds 100 km, the flight test was conducted in the Woomera Test Range in South Australia, one of the largest land-based test ranges in the world (figure 4).

Fig. 4 Woomera Test Range in South Australia

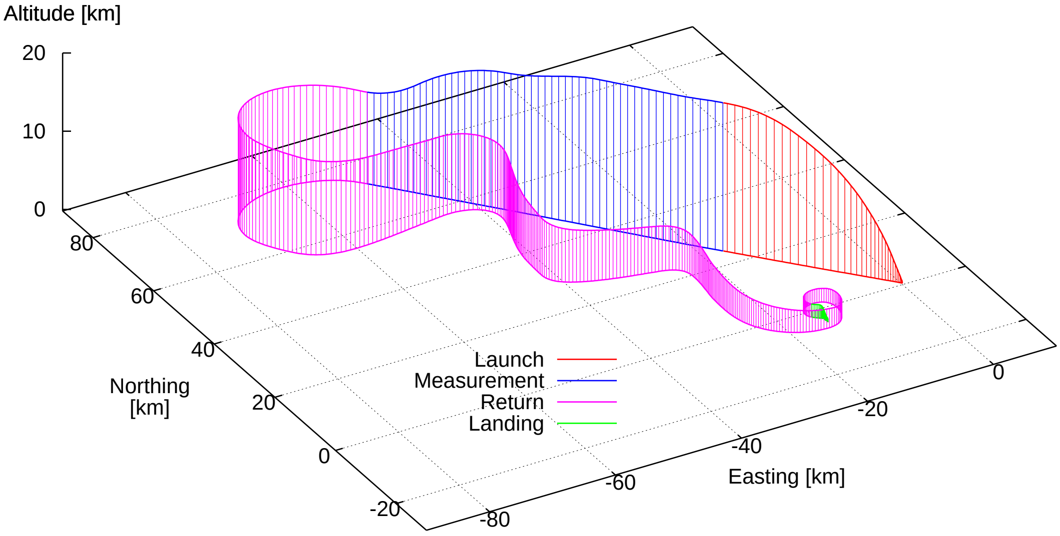

Fig. 5 Flight Trajectory

3 Flight Test Results

The flight test was conducted on October 10, 2005. It was fine weather and the ground wind speed was 5 m/s. The airplane and the booster were launched at 7:06 a.m. local time (figure 6). Subsequent events were performed smoothly as indicated in table 1.

The total flight time was 15 minutes and 22 seconds. The maximum speed, altitude, and down range achieved in the flight test were Mach 2.66, 19 km, and 102 km respectively. The flight trajectory is shown in figure 5, the profile of the airspeed and the altitude is shown in figure 7.

The following sections present the substance of each flight sequence in order.

Table 1 Time Sequence

Time*	Event
0:00	Launch
0:48	Burn out / 180° Roll Over
1:12	Separation
1:45	1st Test Phase at 18 km
2:12	Zero-Lift Dive
2:40	2nd Test Phase at 13 km
2:56	Return Flight
12:58	Parachutes Deploy
14:31	Air Bags Inflation
15:22	Landing

∗ minutes and seconds from the launch

Fig. 6 Launch on October 10, 2005

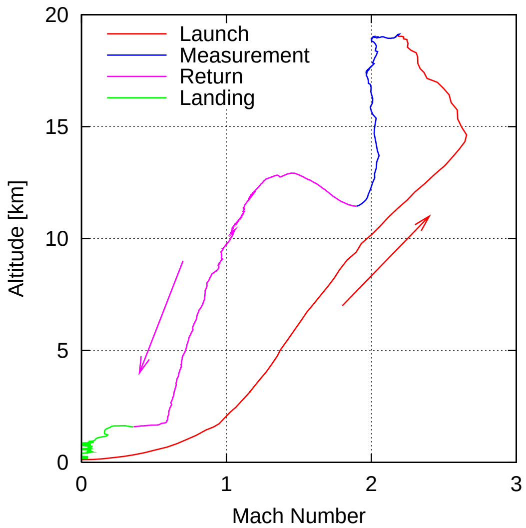

Fig. 7 Speed and Altitude Profiles

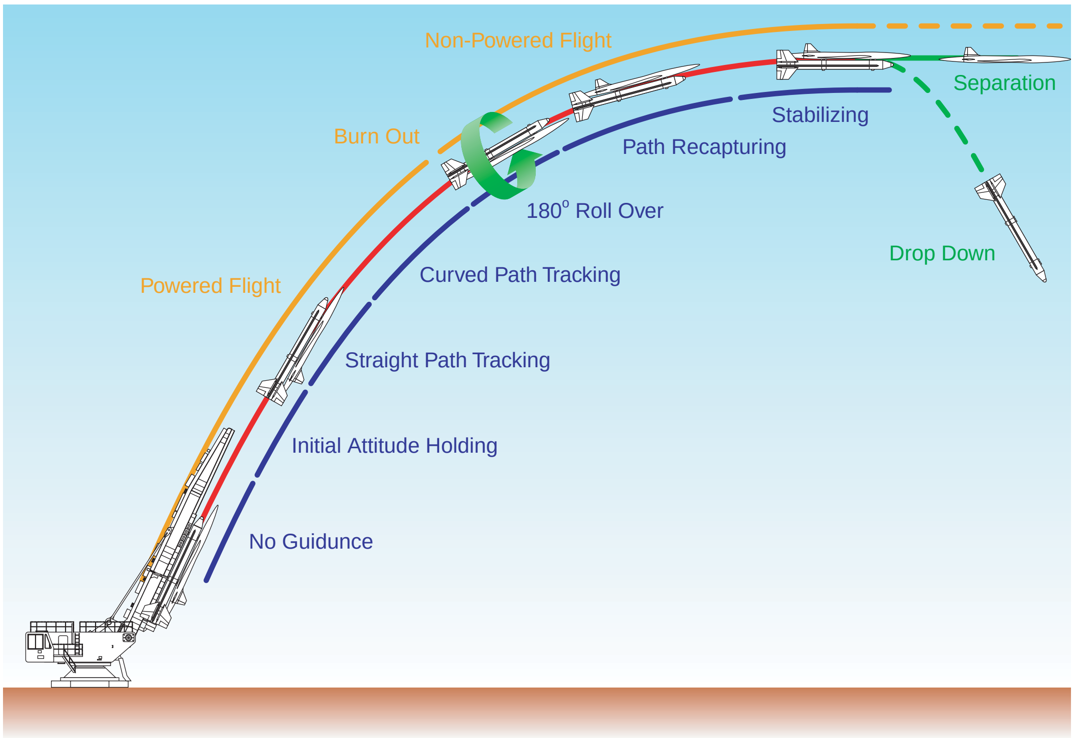

Fig. 8 Boost Phase Sequence

4 Boost Phase

The objective of the booster is to insert the airplane into a required flight condition under various constraints from flight safety, structural strength, etc.

The guidance and control system of the booster consists of an individual flight control computer (FCC), an inertial navigation system (INS), and actuators to drive the control surfaces on four tail fins. The nozzle of the rocket motor is tilted about 3 degrees so that the thrust acts directly on the center of gravity of the combination of the booster and the airplane. The nozzle angle is fixed and the thrust vector is not controllable. Since the flight control is achieved by driving the control surfaces, the controllability is relatively lower just after the launch when the speed is not so high.

Supported by the launcher, the booster attached to the airplane is launched with an elevation angle of 65 degrees (figure 9). If the elevation angle is higher, the airplane and the booster pass through the thick atmosphere in a short time, which is advantageous to their structure. In an emergency, however, a higher elevation angle raises the possibility of flying back toward the control center located at 1 km behind from the launch site. Considering these constraints, the elevation angle was decided.

Until the booster flies out of the launcher, it keeps the control surfaces fixed at each null position to prevent interference with the launcher. Then, it keeps the initial attitude on the launcher in a short time. Accelerated sufficiently, it is guided along a straight path first, and next along a curved path with a radius of 31.5 km, which leads the booster to the target altitude of 19 km. During

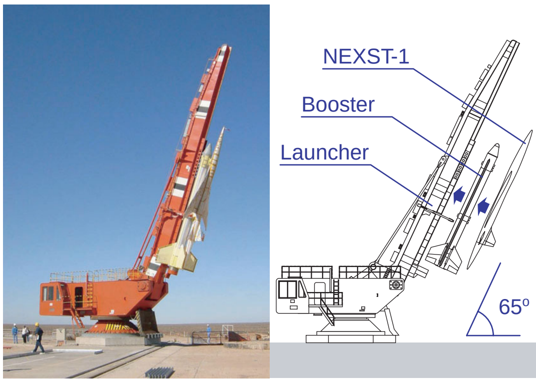

Fig. 9 NEXST-1/Booster on Launcher

this burning period, the airplane is hanging from the rocket upside down.

The solid rocket motor burns about 50 seconds. At the moment of burn out, the speed reaches the maximum in the whole flight sequence. Then, it rolls over 180 degrees because a drag force generated by the booster makes an undesirable pitching moment. The booster recaptures the curved trajectory and climbs toward the target altitude again.

In the actual flight test, the booster climbed smoothly and hit the maximum speed of Mach 2.6 (figures 10, 11). All constraints and requirements were satisfied.

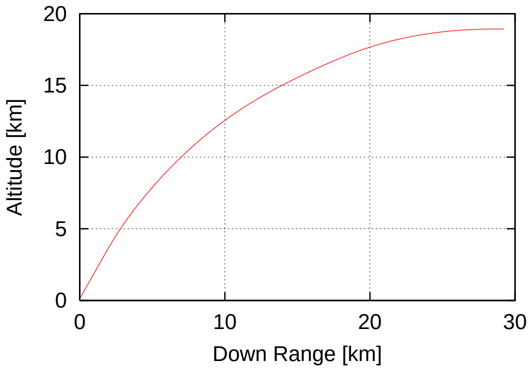

Fig. 10 Ascent Trajectory

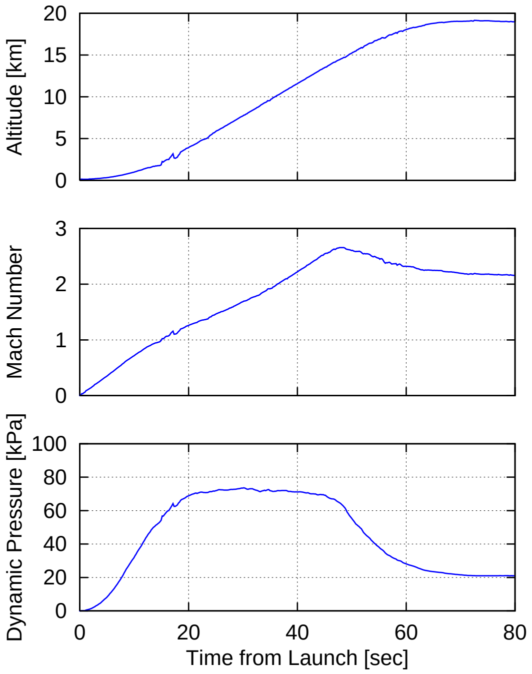

Fig. 11 Profiles of States in Boost Phase

5 Separation

When the booster reaches the target altitude, it concentrates on flight control to make a stable condition suitable for a safe and sure separation. The booster is attached to the airplane by connection bolts at two points in front and in the rear, which are cut off simultaneously. After the cutting off, the booster is not controlled any longer and is forced apart from the airplane by only the gravity and aerodynamic force. Through a large number of mathematical simulations, it is confirmed that a sure separation is performed without any support equipment like springs (figure 12).

An onboard camera, that was installed on the undersurface of the airplane and was facing to the rear side, recorded that the booster separated from the airplane smoothly. Comparing a picture taken by the onboard camera with a simulated vision, the validity of the simulations was verified (figure 13).

The booster had completely performed its duties in 72-second flight and crashed into the desert as planned.

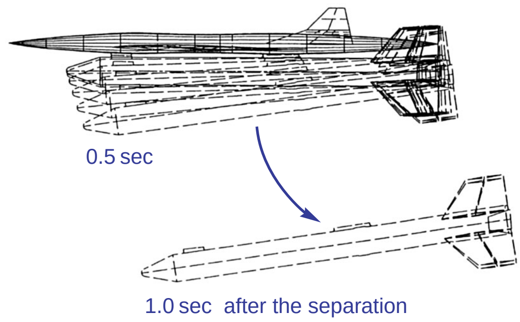

Fig. 12 Example of Separation Simulations

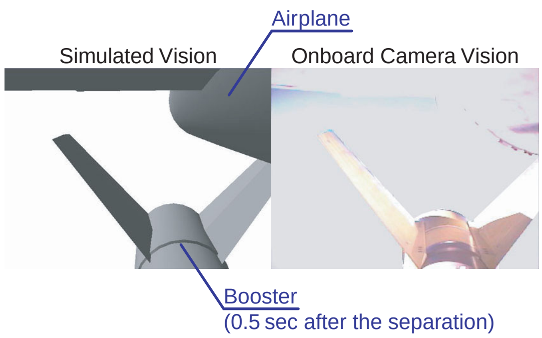

Fig. 13 Comparison between Simulation and Result

6 Measurement Phase

The airplane separated from the booster flies autonomously under its own guidance and control system. Like the booster, the system consists of FCC, INS, and actuators to drive elevators, ailerons, and a rudder. Furthermore, it has an additional high-response vertical accelerometer and an air data system including a five-hole Pitot tube (figure 14). Since the airplane has no thrust equipment, it does nothing but glides.

If the airspeed at the time of the separation is higher than the target speed of Mach 2, the airplane keeps a level flight to decelerate appropriately. At the target speed, the airplane starts the first stage of the measurement phase, in which the angle of attack is changed step by step. In each step, the flight condition is controlled to keep the surface airflow stable.

After the first stage, the airplane plunges into a zero-lift dive to change the target altitude and to recover the speed of Mach 2.

Reaching an altitude of 14 km, the airplane starts the second stage, in which it recovers the lift again and acquires another technical data. Since the wind condition is not so good in the second stage, the angle of attack is not changed step by step, but fixed at one point.

The airplane performed the measurement sequence as expected (figure 15). The target speed of Mach 2 was kept to a tolerance of 0.05, which satisfied the requirement. The stability of the flight condition in each stage and each step was much higher than the requirement, and various high-quality data were acquired.

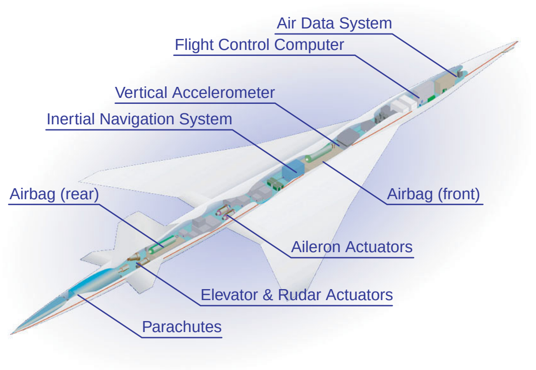

Fig. 14 NEXST-1 Components

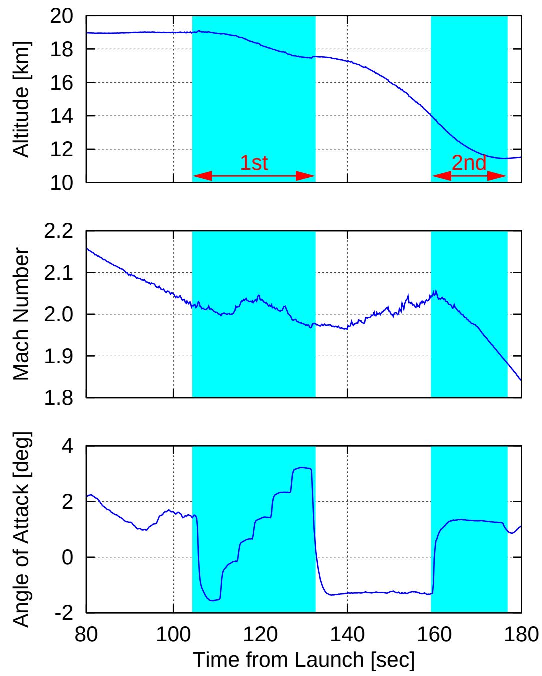

Fig. 15 Profiles of States in Measurement Phase

Using the acquired technical data, detailed analysis to verify the validity of the aerodynamic design, which is a main objective of this project, is now being advanced energetically. Several results have just been reported [1][4].

7 Return Phase

In this return phase, while descending and decelerating, the airplane is guided to a landing area located at 15 km west from the launch site.

After the measurement sequence, the total energy, which is computed from the speed and the altitude, is compared to a reference energy based on the distance to the landing area. The airplane continues to fly ahead away from the landing area until the energy falls below the reference, then it turns the heading toward the landing area.

To extend a flight distance to reduce the speed and altitude further, the airplane performs a series of turns in the return flight after the manner of the space shuttle of NASA. The more energy it has, the deeper it turns.

A series of turns that the airplane performed actually is illustrated in figure 16 and figure 17. Although the airplane was not designed to be guided along a certain trajectory, it was confirmed that the actual flight path corresponded to the one estimated beforehand.

As for vertical guidance, the airplane is controlled to keep a constant dynamic pressure of 20 kPa to descend with an approximately constant rate. Once the airplane arrives at an altitude of 1.7 km, it keeps the altitude and reduces the speed until it reaches a suitable speed for deploying its parachutes.

In the actual return phase, the dynamic pressure or the altitude was held as designed and the speed was reduced sufficiently (figure 18).

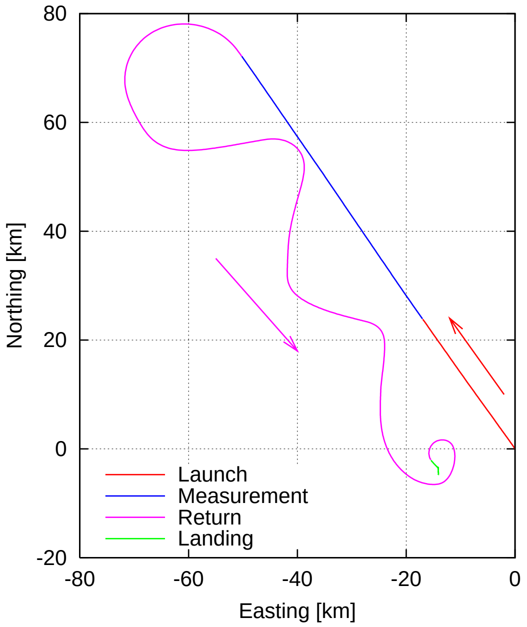

Fig. 16 Return Trajectory

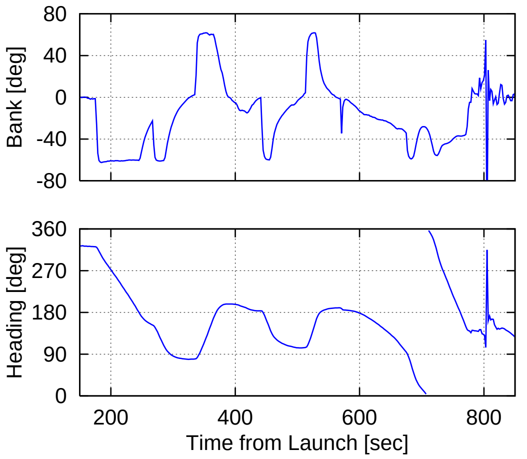

Fig. 17 Attitude Profiles in Return Phase

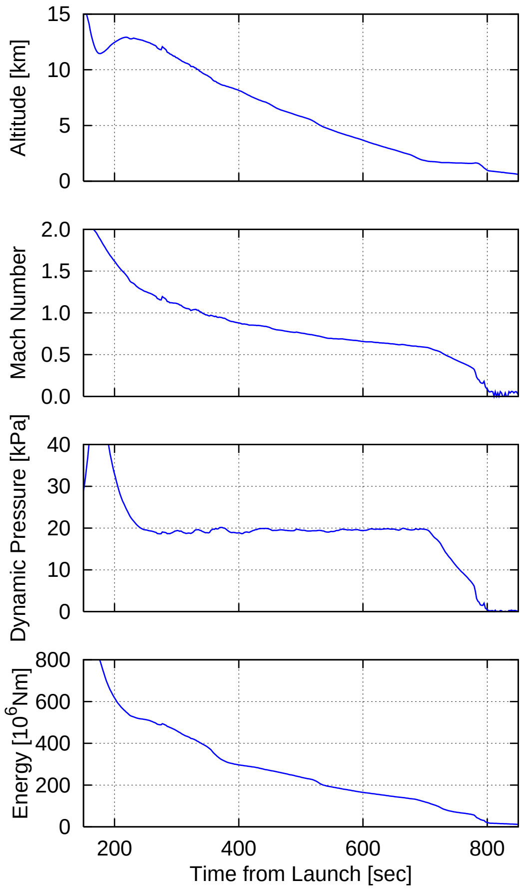

Fig. 18 Profiles of States in Return Phase

8 Landing Phase

While major data acquired in the flight test are transmitted to the ground station in real time, some data are only recorded on the onboard recorder. Therefore, the airplane is required to land softly. An axial shock and a vertical shock are limited to 6 G and 12 G respectively.

When the airplane approaches the landing area and its speed is still higher to deploy the parachutes, it keeps a turn with a radius of 2 km around the landing area. Decelerated to 215 kt (111 m/s), the airplane stops the turns and flies straight. Below 200 kt (103 m/s), it starts a landing sequence by releasing a pilot-chute from its tail cone (figure 19).

The pilot-chute pulls a drogue-chute, which is held narrower at first to soften an axial shock. After the drogue-chute opens fully and the airplane decelerates sufficiently, a three-clustered main-chute is deployed, which is also held narrower. Expanding the drogue-chute and the main-chute in two steps, the axial shocks were suppressed to 3 G (figure 20).

After the main-chute opens fully, the airplane changes its attitude to a level to prepare the landing. Before the landing, two air bags are inflated on the undersurface of the airplane, which reduce a vertical shock at the landing. At last, the airplane landed on the ground without any trouble (figure 21). According to a vertical accelerometer, the vertical shock was suppressed to 10 G. The whole data in the onboard recorder were valid entirely.

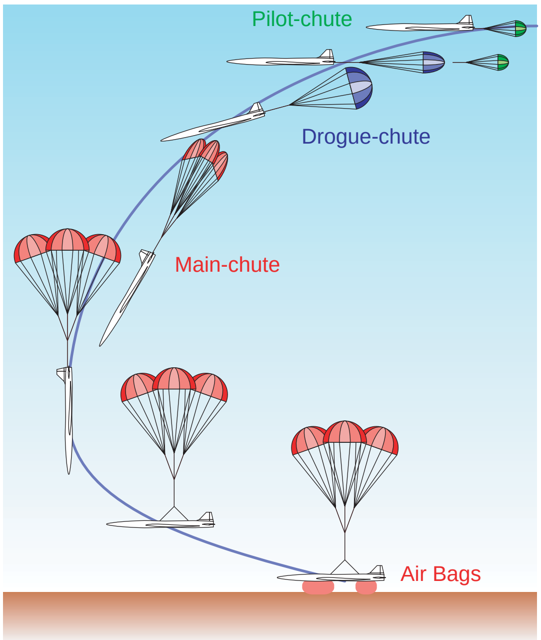

Fig. 19 Landing Sequence

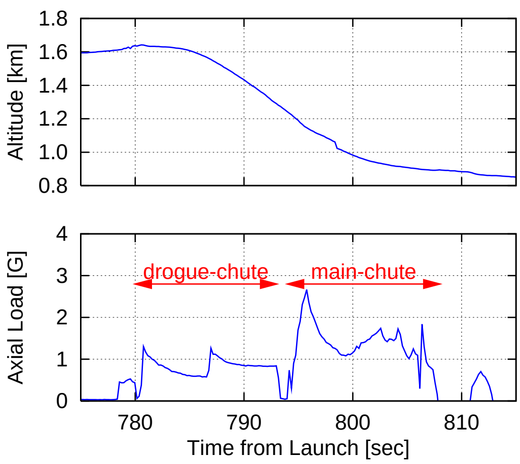

Fig. 20 Axial Load Profiles in Landing Phase

Fig. 21 NEXST-1 Landed on the Desert (orange-colored objects are two air bags)

9 Conclusions

The experimental SST vehicle NEXST-1 was launched on October 10, 2005, in the Woomera Test Range, Australia. It flew at a speed of Mach 2 and acquired a large amount of technical data, which is now used to verify the validity of the aerodynamic design concepts. These data will contribute to the future development of a next generation SST.

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