System design overview of JAXA small supersonic experimental airplane (NEXST-1)

Hikaru Takami
Mitsubishi Heavy Industries, Ltd.
10 Oye, Minato, Nagoya, Aichi 455-8515, Japan

The system of JAXA small supersonic experimental airplane (NEXST-1) has been briefly explained. Some design problems that the designers have encountered have also been briefly explained.

Introduction

Flight experiment of JAXA small supersonic experimental airplane was conducted on October 10, 2005 in southern Australia and was successfully completed obtaining substantial amount of flight data for validation of the aerodynamic performance of the aircraft. In the present paper, the system of the airplane and the system of the rocket that was used to launch the airplane are briefly explained. Several design problems encountered in the design activity are also briefly explained.

Flight experiment

The NEXST-1 flight experiment is schematically shown in Fig.1. The unpowered experiment airplane, which is designed for the minimum supersonic drag with supersonic natural laminar flow concept, is launched on a rocket named NAL-735, which is a derivative of ST-735 originally developed for space purposes. The rocket flies semi-circular trajectory and separates the airplane at speed of slightly above Mach 2 at its culminating altitude of 19 kilometers. After the separation, the airplane executes two blocks of angle-of-attack sweeps while gliding at Mach 2, one at low Reynolds number at altitude of about 18 kilometers and the other at high Reynolds number at altitude of about 12 kilometers.

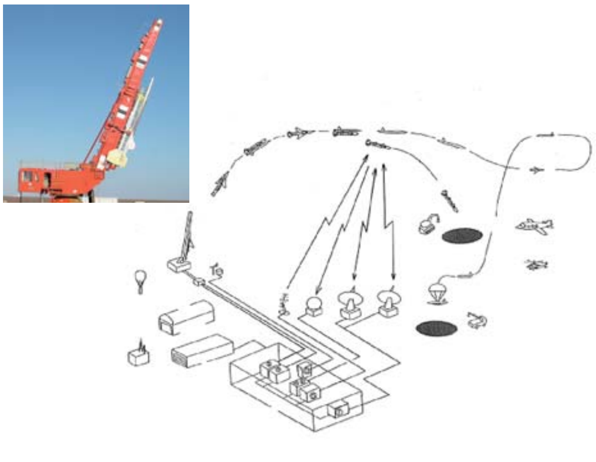


Fig. 1 NEXST-1 flight experiment schematic

After the measurements are completed, the airplane heads back toward a predetermined recovery point, where it deploys parachutes and is recovered.

The flight trial was conducted at Woomera flight test range in southern Australia (Fig. 2), which is famous for various European ballistic missile developments.

Fig. 2 The flight test range

System

Three view drawing is shown in Fig.3. The airplane is mounted on the rocket at two, forward and aft, joints. Four explosive bolts are used, two at the forward joint and the other two at the aft joint. Overall length, width and heights are 11.5, 4.7 and 2.9 meters, respectively. The weight of the airplane is about 1,940 kilograms and that of the rocket is about 5,900 kilograms including propellant.

Each of the airplane and the rocket has its own flight control system and its dedicated flight control equipments such as sensors, flight control computers, actuators and batteries, and has autonomous flight capability. Therefore, the airplane is “the wing structure” of the rocket during the launch phase.

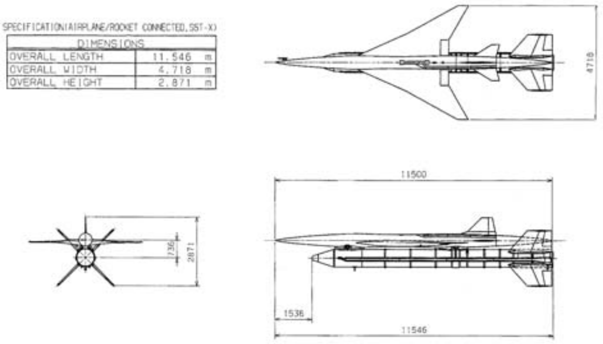


Fig. 3 Three view drawing

The rocket system is shown in Fig. 4. Most of its flight control system equipments and emergency flight termination system equipments are located at the forward portion. Mid portion is the rocket motor case which is a steel-made pressure chamber that contains propellant. Four fins, four independent flight control surfaces, and the actuators are located at the aft portion. The nozzle is canted by 2.9 degrees to minimize undesirable pitching moment around the center of gravity at the initial phase of the launch when the airspeed is low and the rocket control surfaces are ineffective.

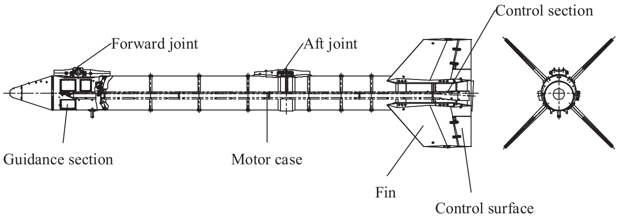


Fig. 4 The rocket system

The airplane system is shown in Fig. 5. The wing has an arrow wing planform, of which sweepback angles are 66 degrees inboard and 61 degrees outboard, respectively. Wing camber is designed for the minimum supersonic lift dependent drag and the thickness distribution is designed to maintain supersonic natural laminar flow at the forward portion of the wing upper surface. Longitudinal static stability is negative at subsonic speed and almost neutral at supersonic speed. Control and damping around roll, pitch, and yaw axes are provided by the flight control system with left and right aileron, all-moving horizontal tail, and rudder. Most of the flight control system equipments are located at the forward portion of the fuselage, instrumentation system equipments and some of flight control system sensors are located at the mid portion, and flight control actuators and recovery parachutes are located at the aft portion. Emergency flight termination is made with a cartridge actuator that forcefully deflects the horizontal tail to full pitch-down position.

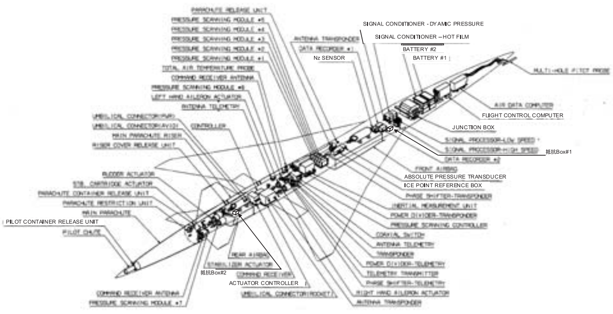


Fig. 5 The airplane system

Design issues

It is common that designers encounter various problems in system development activity. In the present section, some of the problems that the NEXST-1 designers have encountered are briefly explained.

Launch load

At the instant of ignition, internal pressure of the rocket motor increases rapidly and the motor case expands in very short time. In case of NAL-735, the motor case expands by about 2 millimeters in about 30 milliseconds. The motor case expansion combined with rapid thrust increase produces large dynamic load to the structure, especially at the two joints connecting the airplane and the rocket. Another dynamic load occurs when the rocket departs the launcher. These dynamic loads are shown in Fig. 6.

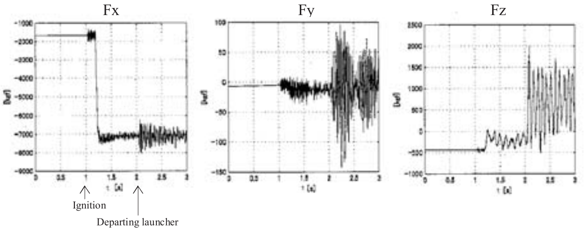


Fig. 6 Launch load, analysis

Detailed analysis has resulted in the conclusion that the previously designed aft joint structure is insufficient to bear the large dynamic load and was modified to a different concept structure in which a hemispherical thrust pin is used to transmit loads between the rocket structure and the airplane structure (Fig. 7). The capability of the modified joint was then verified in the static strength test (Fig. 8).

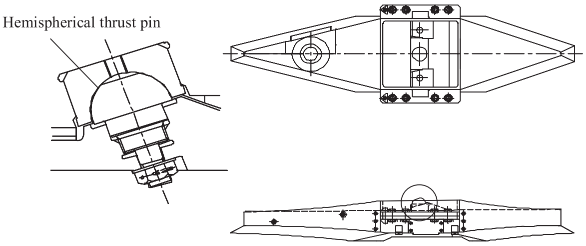


Fig. 7　Redesigned aft joint

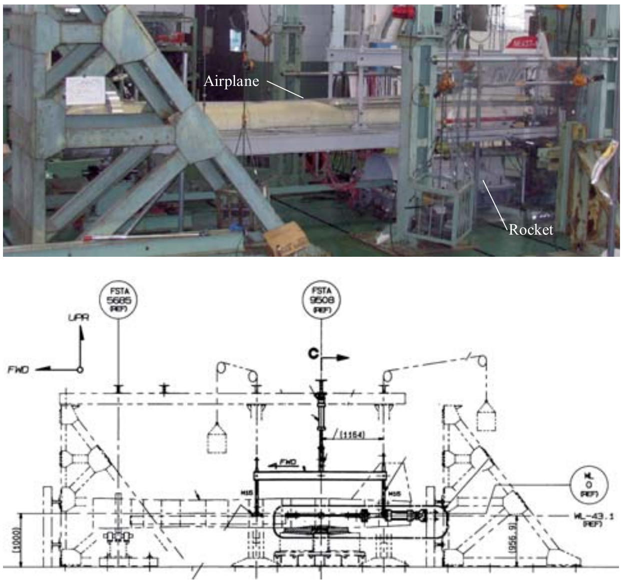


Fig. 8　Static strength test for the aft joint

Combustive oscillation

In the ground combustion test for the NAL-735 rocket motor, combustive oscillation peaking at 73Hz was identified (Fig. 9). It was concerned that vibration environment of onboard equipments may exceed their specification boundaries. Detailed analysis has shown that the structural modes of which frequencies are close to the combustive oscillation frequency increases in their gains resonating with the combustive oscillation in case the longitudinal motion of the forward joint is constrained, for instance, by maneuver loads (Fig. 10).

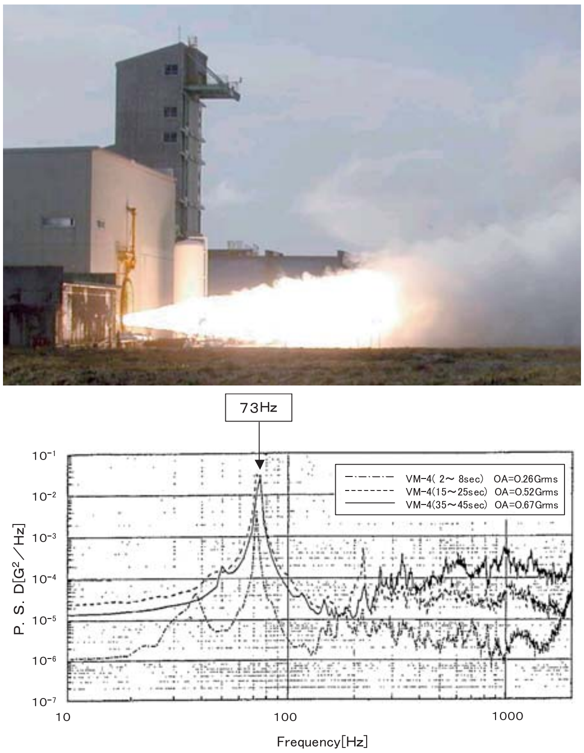


Fig. 9　Combustive oscillation identified in ground combustion test

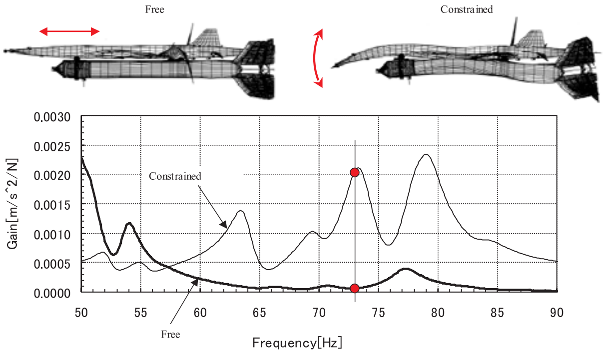


Fig. 10　Frequency responses, forward joint free and constrained

The forward joint initially was designed incorporating a sliding mechanism to absorb the expansion of the rocket motor case at ignition previously mentioned, but was redesigned to multiple links (Fig. 11) to ensure free longitudinal motion at the forward joint in all flight conditions to prevent the structural modes from resonating with the combustive oscillation, hence, to alleviate the vibration environment of onboard equipments.

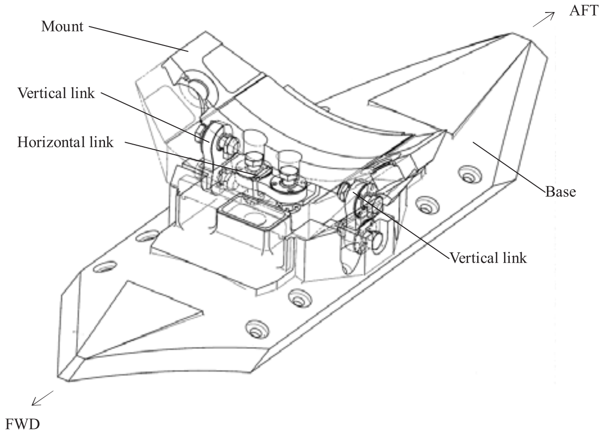


Fig. 11 Redesigned forward joint

Fig. 12 Vibration test for the launch configuration

Flutter

The maximum dynamic pressure during acceleration climb after launch is about 10,000 kilogram per square meter. The dynamic pressure reaches at its maximum after about 15 seconds from the ignition when the airspeed crosses at Mach 1. Flutter analysis has shown that flutter is suspected at this low supersonic and high dynamic pressure speed range because of the lack of torsional stiffness of the aileron structure (Fig. 13). The aileron structure, especially the torque shaft-aileron joint and the torque shaft itself, was modified so that the torsional stiffness is increased sufficiently enough to prevent flutter, and the stiffness improvement was verified in the ground test (Fig. 14). The similar modification was also made to the rudder structure because similar design concept had been used.

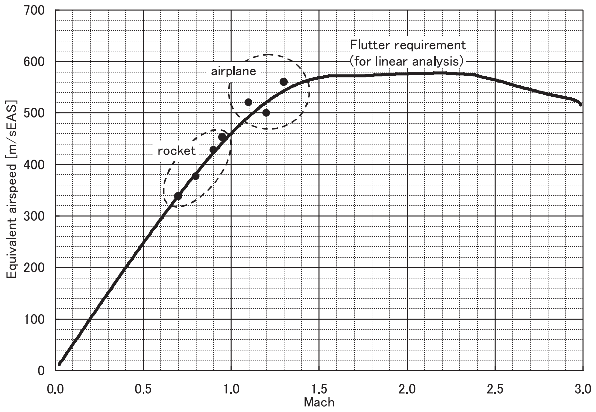


Fig. 13 The result of flutter analysis

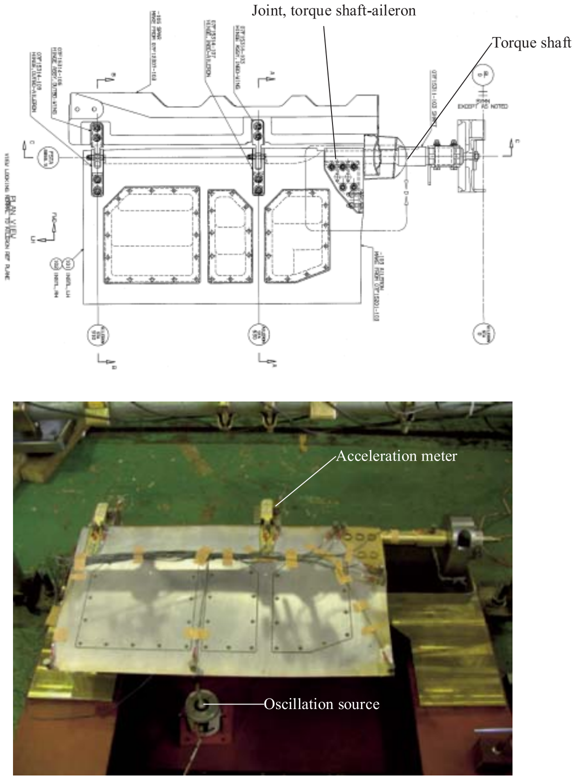
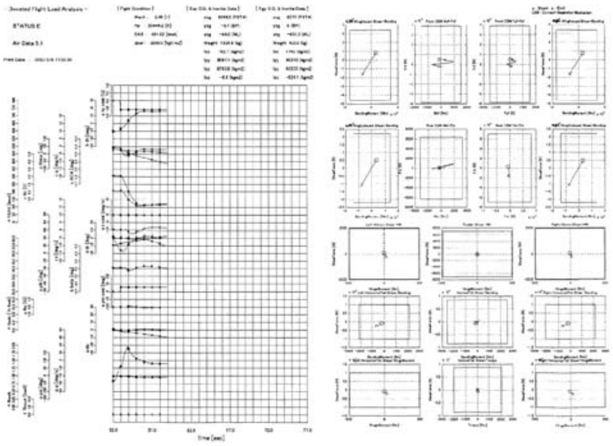


Fig. 14 Redesigned aileron structure and verification test

Flight load

The rocket maneuvers using the airplane as its own wing. Intensive flight load analysis was made in the flight control law development to ensure that the flight load on the aircraft structure lies under its limit loads (Fig. 15). This is very important because unmanned aircraft sometimes makes inadvertently large maneuvers that designers never expect. It was necessary to reduce some flight control gains and add several limiters to the rocket flight control law. The size of some bolts of the joints of the inboard wing and the outboard wing of the airplane were also increased (Fig. 16) because it was judged that excessive reduction of some flight control gains was harmful to the maneuvering capability of the rocket.



Flight characteristics Flight loads

Fig. 15 Flight load simulation

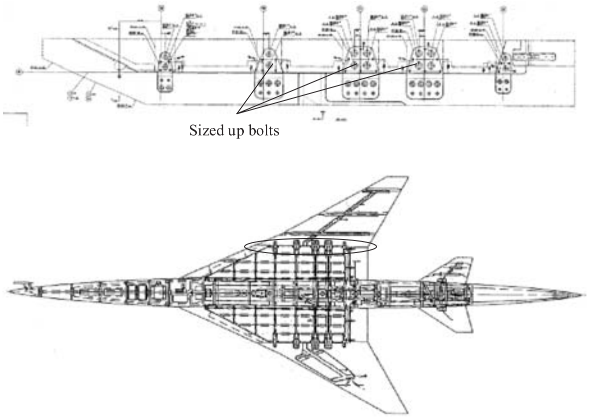


Fig. 16 Reinforced mid-board wing joint

Separation

Separation characteristic is important. Any part of the rocket must not make contact with the airplane structure. Stable flight of the airplane after separation must be ensured. The interactions of shocks emerging from various parts of the rocket and the airplane were assessed in supersonic wind tunnel tests (Fig. 17). The shock emerging from the rocket nose is fairly strong and the pitching moment variation indicates that where on the airplane the shock hits dominates the interaction. In order to suppress the pitch up tendency at the initial moment of separation, the airplane flight control system deflects the horizontal tail by 3 degrees toward nose down direction shortly before separation.

The in-flight separation was beautiful, which was pictured from the chase camera on the ground (Fig. 18).

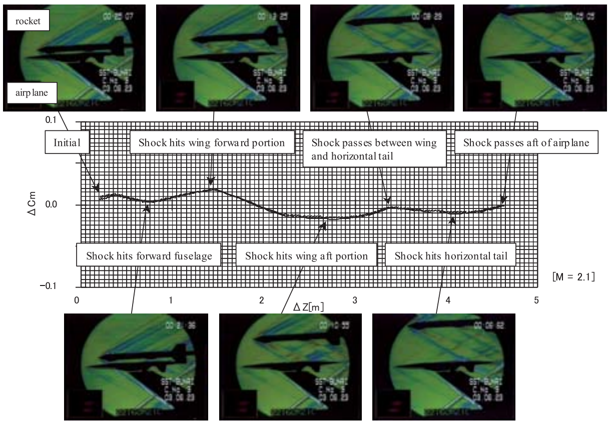
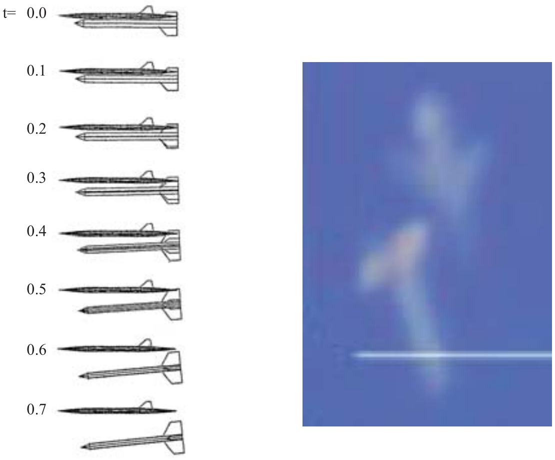


Fig. 17 Wind tunnel test result, interference of the rocket on the airplane



Simulation Flight

Fig. 18 Separation trajectory, simulation and the flight test

Flight control

The schematic of the airplane flight control logic is shown in Fig. 19. Longitudinally, it is a g-command system with pitch stability augmented by pitch rate feedback. The lateral control is a roll rate command system and the directional control is a yaw rate command system. The control gains are scheduled with dynamic pressure and Mach number that are provided by the air-data computer located at the foremost location of the airplane. In the return-to-recovery point phase, the flight control system maneuvers the airplane so that the total energy, that is, the sum of potential energy and kinetic energy decreases along with the predetermined schedule.

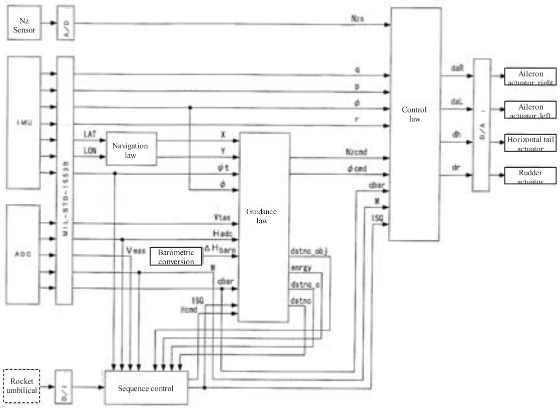


Fig. 19 Schematic of the airplane flight control logic

An interesting feature incorporated to the flight control system is one of its degraded modes called "air data loss mode", in which air data are estimated with the inertia data provided by the inertial measurement unit and the atmospheric wind data kept in the flight control computer installed shortly before launch (Fig. 20). It was never used in the actual flight experiment, but was helpful to prepare for unexpected failure and to increase the probability of the mission success.

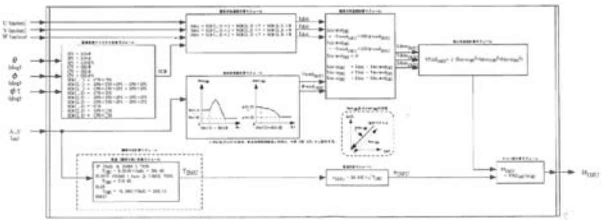
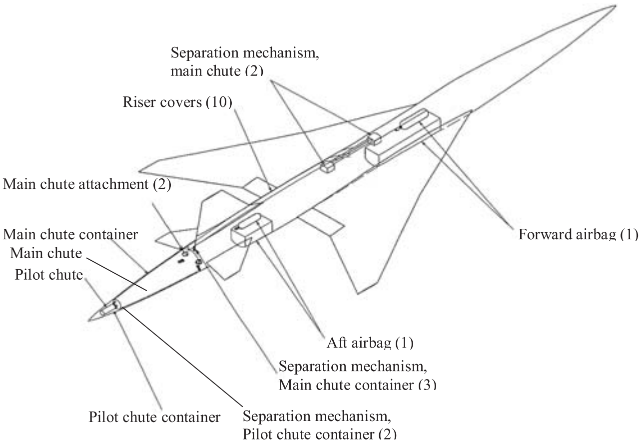


Fig. 20 Air data loss mode logic

Pyrotechnics

On the airplane, many pyrotechnics are used at various locations for the recovery system (Fig. 21). Pyrotechnics have a unique characteristic. They sometimes short-circuit after explosion. Once short-circuit occurs at a cartridge, most of the electric current runs through the shorted circuit and the rest of cartridges never fire. This was initially ignored and later was noticed, and protective resistors were inserted to all the electric power supply lines of the pyrotechnic system.



(Number inside parenthesis is the number of pyrotechnics.)

Fig. 21 Pyrotechnics on the airplane

Summary

In the present paper, the system of JAXA small supersonic experimental airplane (NEXST-1) has been briefly explained and some design issues have also been briefly discussed.

Throughout design process, designers face various problems. Unforeseen problems lie everywhere (Fig. 22). Some are easy to find out solutions and some are so tough that the master schedule must be changed. Sometimes heavy pressure is enforced upon designers trying to make them rush for easier solutions. But it is the sincere attitude, the deep insight, and the strong will of designers that guides a project on the shortest path to the final goal called "success".

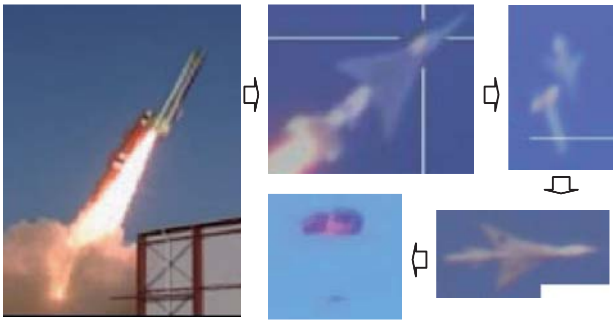


Fig. 22 The flight test photos

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References

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