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D-SEND#2 FLIGHT DEMONSTRATION FOR LOW SONIC BOOM DESIGN TECHNOLOGY

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Abstract

The D-SEND project aims to demonstrate the feasibility of JAXA's low sonic boom design concept through the balloon drop tests. The project is carried out in two phases (D-SEND#1 and D-SEND#2). In the D-SEND#2, an unmanned experimental supersonic airplane based on the JAXA's low sonic boom design concept is newly designed. The sonic boom intensity of the airplane is designed to be almost as half as that of the conventional supersonic transport. The airplane autonomously flies over microphones and the shaped sonic booms are measured. First drop test of the D-SEND#2 was conducted in 2013, but the airplane lost control during the pull up phase at supersonic speed and the airplane could not fly over the microphones. After intensive investigation of the mishap, the aerodynamic data and attitude control law are revised. In 2014, the second flight of the D-SEND#2 is planned. In this paper, the details of the airplane developed in the D-SEND#2, the first flight results and the ongoing second flight preparation are described.

1 Introduction

JAXA (**J**apan **A**erospace E**x**ploration **A**gency) has been promoting a supersonic technology research program since 1997. From 1997 to 2005, the NEXST program had been promoted focusing on the aerodynamic drag reduction technologies. In this program, an unmanned experimental supersonic airplane was developed and its flight trial called "NEXST-1 project" was conducted at Woomera Prohibited Area of Australia in 2005[1]. In 2006, a new program called "S3 program" (**S**ilent **S**uper**S**onic research Program) has started as a post program of the NEXST program[2]. The S3 program contains not only basic researches on supersonic aircraft technologies but also flight demonstration project. In this program, JAXA has been focusing on the technology of the computational fluid dynamics such as the aerodynamic drag reduction and sonic boom reduction. In 2010, JAXA launched a new project called "D-SEND (**Dr**op test for **S**implified **E**valuation of **N**on-symmetrically **D**istributed sonic boom)" as one of the flight demonstrations, aiming at verifying JAXA's aerial sonic boom measurement system [3],[4] and proprietary low sonic boom design concept [5]. Since the D-SEND project utilizes the high altitude balloon free fall technique to realize a supersonic speed of the test body, a jet engine is not installed on the test body. This enables us to develop a small unpowered test body and provides the relatively low development cost and shorter term of the development.

The drop tests are planned to take place at Esrange space center in Sweden. The Esrange space center is supervised by SSC(**S**wedish **S**pace **C**orporation) which has years of expertise in the field of balloon operations. In the drop tests, a large stratospheric balloon lifts the test bodies up to an altitude of about 30km. After reaching the ceiling, the drop bodies are released and the sonic booms generated by the bodies are measured by microphones at several altitudes up to 1km. The microphones and the data recording systems are hung along the tether line of a blimp which stays at 1km altitude.

The drop tests sequences of the D-SEND#1 and D-SEND#2 are illustrated together in Fig.1. The sequence starts from the left. The two axisymmetrical bodies of the D-SEND#1 simply free-fall from a high altitude balloon and go through at supersonic speed near the sonic boom measurement system. On the other hand, an unmanned experimental supersonic airplane (S3CM: **S**ilent **S**uper**S**onic **C**oncept **M**odel) flies over the sonic boom measurement system at required flights conditions. JAXA's low sonic boom design technologies will be validated by measuring the shaped sonic booms which the S3CM generates. This aerial sonic boom measurement technique and the measured low sonic boom data will contribute to establish a sonic boom acceptance rule for the supersonic transport overland of the International Civil Aviation Organization (ICAO).

The D-SEND#1 drop tests were conducted twice in May 2011. The two different axisymmetric bodies were dropped from the balloon at 30km altitude and the conventional N-type and the shaped sonic booms were successfully captured by microphones at multiple altitudes up to 1km[6],[7].

In this paper, the details of the airplane developed in the D-SEND#2, the first flight results of the D-SEND#2 and the ongoing second flight preparation are described.

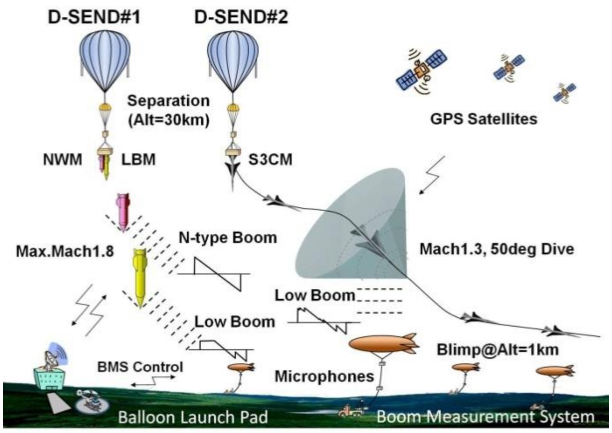

Fig.1 D-SEND#1&#2 Drop Tests Sequences

2 D-SEND#2 Drop Test

2.1 Test Sequence

The detailed drop test sequence is as follows:

(1)Hanging upside down from the gondola of a stratospheric balloon, the airplane is launched and ascends to an altitude of about 30km in order to acquire the energy of supersonic flight.

(2)The balloon with the airplane flies horizontally until it reaches the separation zone.

(3)The airplane is released from the balloon by a command from the ground after it enters the separation zone(these are two donut-shaped separation areas in the test zone).

(4)The airplane is accelerated by free fall to supersonic speed, pulled up from a vertical orientation and autonomously guided toward one of the boom measurement systems[8].

(5)The airplane flies over the boom measurement system at Mach 1.3 and a flight path angle of 50 degrees in order to propagate its shock waves vertically to the ground. On the ground, the several microphones of the sonic boom measurement system capture the sonic booms.

(6)The airplane is autonomously terminated and crashes into the test zone after it flies over the sonic boom measurement system.

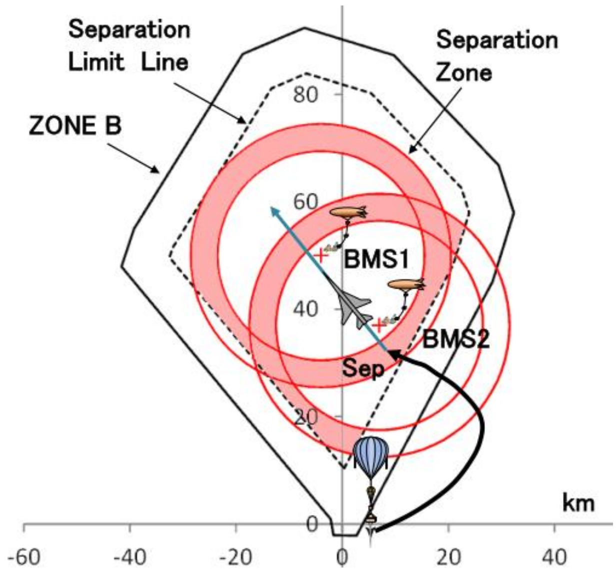

Fig.2 Balloon Trajectory and BMS Layout

2.2 S3CM Design

Since this test utilizes the balloon test technique, there are two restrictions when the dimension of S3CM is designed. The total length of the body has to be below 8m and the weight to be below 1500kg. Therefore, the S3CM is set to be 16%

scale of JAXA's small supersonic transport as a technical reference airplane[2], and as a result, the final specifications are set as follows: the total length is 7.913 m, the wing span is 3.510 m, the wing area is 4.891 m2 and the total weight is 1000 kg.

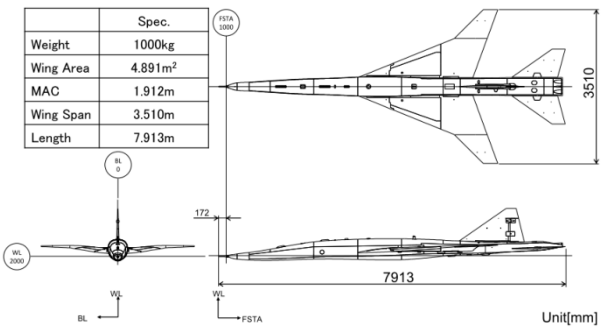

Fig.3 Three View Drawing of S3CM

The rudder and stabilators (differential) are used for the flight control. After the separation from the balloon, the flight control computer autonomously controls all flight sequences, and the airplane flies over the boom measurement system at design conditions. The onboard sensors for the flight control are an embedded GPS/INS, an air data system and a high-accuracy Az accelerometer. The components layout is illustrated in Fig.4.

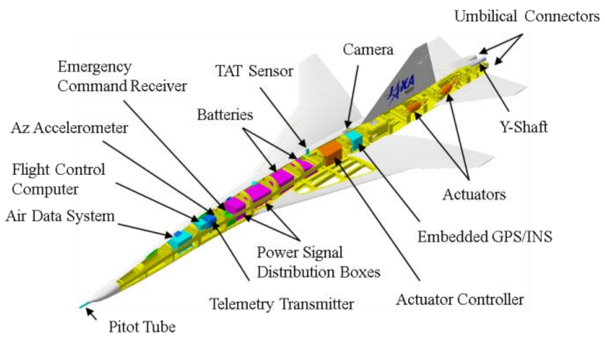

Fig.4 S3CM Components Layout

The main structures are made from aluminum alloy. The manufactured outer shape of the main wing has a jig shape. The jig shape is designed so that the deformed shape due to the dynamic pressure at the time of measurement of the sonic boom can be formed into the designed aerodynamic shape. Two S3CM were manufactured for two balloon drop tests.

2.3 Low Sonic Boom Design

When an airplane at supersonic speed, it generates many shock waves form the nose, wing, engine and so on. On the ground, these shock waves have a conventional pressure signature (N-type), which has two sudden pressure rises. This signature has a thunder-like sound called a sonic boom.

JAXA has been conducting R&D to halve the intensity of the sonic boom using CFD technology. The design concepts applied to the D-SEND#2 airplane are as follows (Fig.5):

- Front shock tailoring by non-axisymmetrical nose
- Aft shock tailoring by lifting aft-fuselage
- Low-drag/low-boom wing by multi-objective optimization
- Inversely cambered stabilator for low-boom and trim characteristics

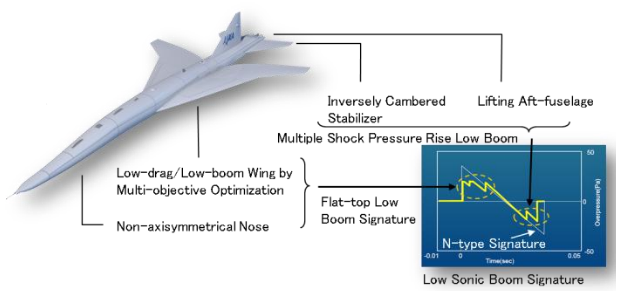

Fig.5 JAXA's Low Boom Design Concepts

The sonic boom signature at the design point (Mach=1.3, CL=0.12) is shown in Fig.6. The green line is the predicted shaped sonic boom signature. The N-Type signature calculated by first cut method is also shown in the same figure for a reference. The sonic boom intensity of S3CM is designed almost as half as the reference signature. The predicted sonic boom signature is calculated by JAXA's numerical code called "Xnoise", which utilizes the augmented Burgers equation combined with the ray tracing. The effects of nonlinearity, geometrical spreading, inhomogeneity of atmosphere, thermoviscous attenuation, molecular vibration relaxation and winds are taken into account [9].

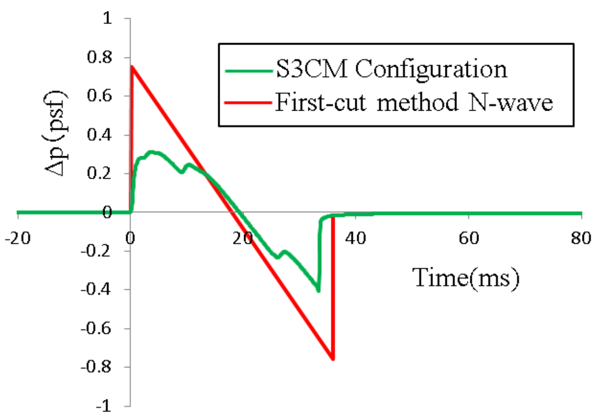

Fig.6 Shaped Sonic Boom Signature of S3CM

2.4 Boom Measurement System (BMS)

Boom Measurement System is a system for measuring sonic booms on and above the ground. BMS consists of three sub-systems, namely Airborne Blimp Boom Acquisition (ABBA) System, Ground Measurement System, and BMS Control System. The schematic overview of the BMS is shown in Fig.7. Taking account the possible balloon trajectories in the campaign season, the measurement sites(North, Center and South) are selected and the measurement systems are placed in each sites.

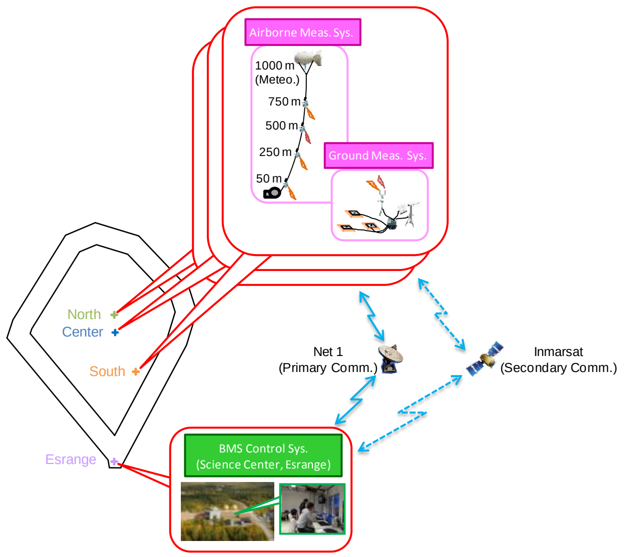

Fig.7 Schematic Overview of BMS

2.4.1 ABBA System(ABBAS)

ABBA System consists of a blimp system and a measurement system. The blimp system includes a blimp (Aerostar TIF-6500), helium gas, a tether, a winch and other materials related to the blimp. The blimp system is prepared and operated by SSC. The measurement system consists of a meteorological observation system and airborne sonic boom measurement systems. One meteorological observation system and three airborne sonic boom measurement systems are installed to the blimp system. The meteorological observation system is attached to the payload lines of the blimp. The airborne sonic boom measurement systems are installed to the tether at an altitude of 750, 500, 250, and 50 m.

Fig.8 Blimp Operation Training

2.4.2 Ground Measurement System(GMS)

Ground Measurement System is used for measurement of sonic booms on the ground, meteorological observation on the ground, and communication between GMS and ABBAS as well as between GMS and BCS at Esrange space center. For the sonic boom measurement, three aluminum ground boards (1m x 1m) with a microphone are placed at intervals of several meters.

2.4.3 BMS Control System(BCS)

BMS Control System is installed in the payload control center near the balloon launch site in Esrange space center. The system is used for remotely controlling and monitoring the GMS and ABBAS operated in three measurement sites. For communicating with them, a commercial network and Inmarsat BGAN systems are used for redundancy.

3 Drop Tests

3.1 First Drop Test

The first drop test of the D-SEND#2 was conducted on 16th of August in 2013 in ESRANGE space center. The balloon launch was successfully performed (Fig.9&Fig.10). After the balloon reached at an altitude of about 30km, the airplane was released from the balloon. Fig.11 shows the separation from the gondola view.

Just after the airplane reached maximum speed Mach 1.6 at an altitude of 23km, the rolling and yawing motions started and then amplified gradually. Eventually, the airplane attitude control went out of control at 64sec from the separation. The airplane fell in a spin and recovered its attitude control at an altitude of about 5km in a subsonic speed. Although the airplane headed toward the target BMS site, that was too late and the airplane could not fly over the targeted BMS site. BMS just recorded the sonic boom generated during the freefall attitude. The flight path is shown in Fig.12.

In this first campaign, two airplanes were assembled and ready to flight, but the second drop test was cancelled due to this failure.

Fig.9 Balloon Launch Vehicle with S3CM

Fig.10 Balloon Launching

Fig.11 S3CM Separation (Gondola View)

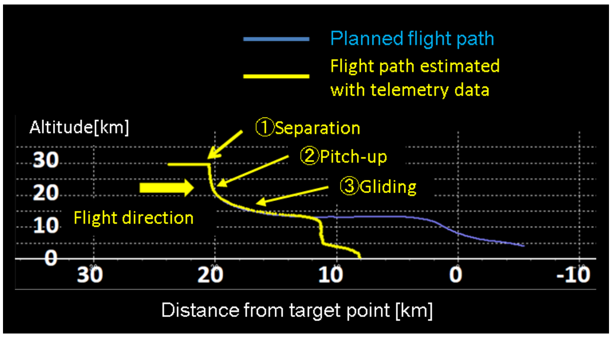

Fig.12 Flight Path of First Drop Test

3.2 Return to Flight

It took three months for us to investigate the reasons of the failure. Finally, it was found out that some aerodynamic characteristics of the airplane exceeded the designed range of aerodynamic uncertainties and the attitude control software did not have enough stability margin to compensate the aerodynamic uncertainties.

The aerodynamic characteristics including its uncertainties are modified through additional CFD analysis and wind tunnel tests. The attitude control law is also modified to have more stability margin than the previous one by taking account the modified aerodynamic characteristics. Fortunately, there was no need to modify the outer shape of the airplane and other hardware. Just the onboard software is modified and From June in 2014, we have returned to ESRANGE space center and started to prepare the next drop test[10]. The flight results including the sonic boom data will be shown on the day of the presentation.

Fig.11 S3CM System Function Test

4 Conclusion

D-SEND#2 drop test is overviewed and the design of the experimental airplane(S3CM) are described. After the first drop test failed, the second drop test is planned again and JAXA is now preparing for the second flight in ESRANGE space center.

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