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

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1. Overview of Supersonic Research Programs

(1) **NEXST-1 Project** (1997-2005) in NEXST Program

   - D-SEND#1 - two drop tests (2011): success
   - D-SEND#2 - 1st flight test (2013): failure

   - Principal test results → Goal of S3 program

Concluding Remarks
To address the technological challenges to create a next generation SST beyond Concorde, JAXA focused on the following R&D areas:

**Economically Viable**
- Drag Reduction (Supersonic Cruise)
  - NEXST Project (1997-2005)

**Environmentally Acceptable**
- Low Sonic Boom
  - D-SEND Project (2010-2015)
- Low Noise (Take-off/Landing)
  - Flight Test Demonstration Project
  - S3 Program (2006-2015)
Supersonic Research Programs

National Experiments Supersonic Transport Program
NEXST Program

Silent Supersonic Tech. Research Program
S3 Program


D-SEND Project

1st Trial: Success
2nd Trial: Success
3rd Trial: Success

1st Trial: Failure

Feasibility Study

Planning of New Flight Demonstration Project

Cancelled

Design Phase

Design/Development

Improvements

Non-Powered Drop from Balloon

Supersonic NLF Wing Design Concept
(Ref.: ICAS2010, 2012)

Low Boom Design Concept
(Ref.: ICAS2012, 2014, 2016)

Low Drag Technology

Low Boom/Low Drag Technology
Overview of NEXST Program

Technical Target: Aircraft: Larger SST than Concorde

Specifications of Target Aircraft:
- Cruise Mach: 2.0
- Length: 91 m
- Wing Area: 836 m²
- Max. Weight: 360 t
- Pax: 300
- Range: 11,000 km

Specifications of NEXST-1 (11% scale):
- Flight Mach: 2.0
- Length: 11.5 m (adding parachute space)
- Wing Area: 10 m²
- Max. Weight: 2 t

Objective:
To develop a CFD-based aerodynamic design method including new drag reduction concepts.
Surface roughness target: **0.3μm**

Natural Laminar Flow (NLF) Wing to reduce friction drag

Cranked Arrow Planform to reduce lift-dependent drag

Area-ruled Body to reduce wave drag due to volume

Warped Wing to reduce lift-dependent drag

[Design Point]
M=2, $C_L=0.1$ @ H=18km

[1% scale of a large SST (300pax)]
Length: 11.5m, Span: 4.72m, Weight: 2000kg

[Design Point]
M=2, $C_L=0.1$ @ H=18km

[1% scale of a large SST (300pax)]
Length: 11.5m, Span: 4.72m, Weight: 2000kg
NEXST-1 Design Procedure

CFD-based Inverse Design Flow

\[ \Delta C_p = C_{p_{\text{lower}}} - C_{p_{\text{upper}}} \]

Ideal \( C_p \) for NLF

Target \( C_p \)

Ideal load by warp design

Initial configuration using a warped wing and area-ruled body concepts

successive approach

- Computation by CFD
- Estimate \( C_p \)-difference
- Modification of shape

Designed airfoil geometry

final

initial
NEXST-1 1st Flight Test

July 14th, 2002

Separation system operated

Rocket and NEXST-1 vehicle collided

NEXST-1 vehicle dropped
Main Cause of the Failure

Shock of ignition

Gap was kept.

between board and harness

Successful vibration test (But, AP axis was oriented horizontally)

No vibration test vertically

Spring deformed by weight of AP

Shock of ignition

Gap was lost.

Electrical short

separation signal
Main Cause of the Failure

- After that, **about 300 items** of all the NEXST-1 vehicle system were thoroughly checked and modified.

- In the aerodynamic measurement system, we also found **two big issues**.
  1. An excessive **response delay** in the pressure measurement system
  2. Too much **electrical noise** in the transition measurement system

---

Successful vibration test (But, AP axis was oriented horizontally)

Shock of ignition

No vibration test vertically

Spring deformed by weight of AP

Gap was lost.

Electrical short

Separation signal

Main Cause of the Failure

Shock mount

Shock of ignition

Acceleration

Spring deformed by weight of AP

Electrical short

Separation signal

Main Cause of the Failure

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NEXST-1 Flight Test Trajectory

- Measurement
  - H=13.7~11.5 @ M=2, C_L=0.1
  - α=-1.5~3.5 @ M=2
- 19km
- Test 1 α- sweep
- Test 2 Re-sweep
- Separation

Max. Speed: M2.7
Max. Altitude: 19km
Max. Distance: 102km

Oct. 10, 2005 at Woomera
Flight Test Results: Pressure Data

Design Point:
\( \alpha = 1.53 \text{deg} \ (4\text{th step}), \ Re = 14.9 \times 10^6 \)

Flight Test Results: Pressure Data

- \( \eta = 0.3 \)
- \( \eta = 0.5 \)
- \( \eta = 0.7 \)
Laminar and transition flow was achieved over about 40% of the upper surface.

“End of transition” estimated by transition measurements.
NEXST-1 : Effect on a Large SST

Δ(L/D): 13% improvement

L/D=8.81
L/D=7.81
L/D=7.30

Concorde-based configuration (0%NLF) (w/o propulsion)

Full size SST (30%NLF )

NEXST-1 (40%NLF )
Silent SuperSonic Technology Research (S3) program

Technical Target Aircraft: Smaller SST than Concorde

Specifications of Target Aircraft:
- Cruise Mach: 1.6
- Fuselage Length: 47.8 m
- Wing Span: 23.6 m
- Wing Area: 175 m²
- Max. Weight: 70 t
- Range: 3500 nm
- Pax.: 36~50

Objective:
To research & develop some technologies to achieve these target values

<table>
<thead>
<tr>
<th>Technical Challenges</th>
<th>Target Values</th>
</tr>
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<tbody>
<tr>
<td>Sonic Boom Reduction</td>
<td>&lt;25% intensity of Concorde’s boom</td>
</tr>
<tr>
<td>L/D Improvement</td>
<td>&gt; 8 @ cruise</td>
</tr>
<tr>
<td>Structural Weight Reduction</td>
<td>15% ref. to Concorde tech.</td>
</tr>
<tr>
<td>Noise Reduction</td>
<td>meet to Chap.4 with margin</td>
</tr>
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</table>
JAXA’s low-boom design concepts

S3 Concept Model (S3CM)

[Design Point]
\[ M=1.3, C_L=0.12 \]

- Weight: 1000kg
- Wing Area: 4.891m²
- MAC: 1.912m
- Wing Span: 3.510m
- Length: 7.913m

Non-axisymmetrical Nose

Highly warped wing

Lifting Aft-fuselage

Inversely Cambered Stabilizer

Waviness of Lower Surface of Aft-fuselage
Current low boom design theory can create an aircraft design that has low front and rear overpressures, but it cannot keep the trim condition.

As a first step, the front boom reduction was demonstrated in the SSBD program in the US, 2003 (©). JAXA created new design concepts to reduce both front and rear overpressures keeping the trim condition completely.

D-SEND#2 flight test was planned to demonstrate the concepts.

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Concorde

(Front boom reduction)

D-SEND#2
Both front and rear boom reduction at trim condition
D-SEND Project (2010-2015)

Drop test for Simplified Evaluation of Non-symmetrically Distributed sonic boom

(1) D-SEND#1: To establish airborne sonic boom measurement system (BMS)
(2) D-SEND#2: To validate JAXA’s low-boom design concepts
History of D-SEND#2 Flight Tests

1st Flight Test
1st CPN
8/16

2nd Flight Test
2nd CPN
8/22

3rd Flight Test
3rd CPN
7/24

Failure
Analysis of failure

Improvements
- Small stability margin
- Insufficient Aero. Model

No weather cond.

Analysis of FLT data
Success

Discussion of significance & technical value

New ideas to increase the possibility of FLT test

Flight Demonstration of Low Boom Design Concepts
1st Campaign (16 August, 2013)

Flight Path

Uncontrollable flight path

Oscillation (42 sec)

Uncontrollable (62 sec)

Boom propagation

Altitude (km)

Down range (km)
Main Causes of the Failure

Main cause 1
• There was not enough stability margin in attitude control.
  □ The aileron control gain margin was +2dB, which was smaller than the usual margin of +6dB.

Main cause 2
• Lateral aerodynamic characteristics used by the OFP had some errors.
  □ They were mainly based on insufficient correction for the W/T model support-sting.
Weather Conditions for Flight

- Wind speed & direction at ground
- Wind speed & direction at 200m above the pad
- Wind speed & direction at high altitudes
- Wind speed at 1000m at BMS
- No rain
- No fog

at Esrange in Sweden
Sonic Boom measurements were successful at Esrange in Sweden.
Flight path

- Acceleration phase
- Glide phase
- Dive phase
- Measurement phase

Altitude [km]

Distance from BMS [km]

direct
reflected

Blimp (15m)

Blimp @1000m
Mic.
750m
650m
500m
50m
Ground
Target BMS site (N-site) 750m mic.

Overpressure [Pa]

Time [sec]

N-wave

Glide phase Direct

M=1.387
α=7.47deg
δs=1.810deg
H=12.83km

U-wave

Dive phase Direct

M=1.271
α=3.83deg
δs=7.47deg
H=11.91km

Meas. phase Direct

M=1.386
α=4.72deg
δs=1.01deg
H=8.01km

Meas. phase Reflected

M=1.386
α=4.72deg
δs=1.01deg
H=8.01km

Glide phase Reflected

M=1.4
α=5.14deg
δs=1.44deg
H=12.91km

Dive phase Reflected

M=1.271
α=3.83deg
δs=7.47deg
H=11.73km

Time 0 = 2015/07/24 08:02:10 (UTC)
Reduction of peak overpressure

Reference SST w/o low boom design concepts (predicted)

D-SEND#2 (predicted)

D-SEND#2 (measured)

Microphone at 750m

Overpressure [Pa]

Time [sec]
Atmospheric turbulence

Both time and space-wise fluctuations in aerial speed and temperature of the atmosphere

- Turbulence layer
  - Thickness: $\delta$
  - Velocity variation: $\sigma$
  - Random Fourier modes expansion in velocity fluctuation

- Turbulence scale: $L$

- Shock wave
- Pressure signature
  - SST
  - Ray $p$
Atmospheric turbulence

Both time and space-wise fluctuations in aerial speed and temperature of the atmosphere

- Major parameters of the turbulence model estimated using observation data
  - velocity variance \[ \sigma=1\text{m/s} \]
  - turbulence scale \[ L=30\text{m} \]
  - thickness of turbulence layer \[ \delta=3.5\text{km} \]

Low boom signatures at measurement phase

Different turbulent state along spanwise direction.

Propagation direction
Atmospheric turbulence

- Both time and space-wise fluctuations in aerial speed and temperature of the atmosphere

- Major parameters of the turbulence model estimated using observation data
  - velocity variance $\sigma = 1 \text{m/s}$
  - turbulence scale $L = 30 \text{m}$
  - thickness of turbulence layer $\delta = 3.5 \text{km}$

Low boom signatures at measurement phase
Atmospheric turbulence

Both time and space-wise fluctuations in aerial speed and temperature of the atmosphere

- Major parameters of the turbulence model estimated using observation data
  - velocity variance \( \sigma = 1 \text{ m/s} \)
  - turbulence scale \( L = 30 \text{ m} \)
  - thickness of turbulence layer \( \delta = 3.5 \text{ km} \)

The measured signature does not lie within the envelope of all the predicted signatures.

The measured signature lies within the envelope of all the predicted signatures.

All the predicted signatures by turbulence model (about 400 spanwise stations)
D-SEND#2 Flight Test Results (5/5)

Flight path

Overpressure [Pa]

-10
-5
0
5
10

Time [sec]

-0.02
-0.01
0
0.01
0.02
0.03
0.04

σ=1m/s, L=30m, δ=3.5km

D-SEND#2 (measured)

Predicted by turbulence model

750m

650m

500m

mic.
A conceptual design configuration satisfied the 4 targets.

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<th>Results for targets</th>
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<td>22Pa &lt; 25Pa (=25% of the boom by Concorde)</td>
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<td>L/D Improvement</td>
<td>8.1 @ M=1.6 cruise</td>
</tr>
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<td>Structural Weight Reduction</td>
<td>15.3 % (ref. to Concorde tech.)</td>
</tr>
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<td>Noise Reduction</td>
<td>Chap.4 with +4dB margin</td>
</tr>
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Concorde: M=2.0, L=62m, Pax=100

JAXA-SST: M=1.6, L=53m, Pax=50
The acceptance levels for take-off and landing noise have recently been revised by ICAO.

The next generation SST will have to satisfy more severe requirements than the Chapter 4.

We have to revise our conceptual design to integrate new concepts to reduce the noise.
Concluding Remarks

The D-SEND#2 flight test was successfully conducted on July 24, 2015. JAXA’s low boom design concepts were validated in the flight test considering the atmospheric turbulence effect.

Consequently, JAXA was able to design a conceptual configuration that satisfied the technical target values.

In order to clear the path toward a future SST, JAXA will advance research activities including international collaborations and continue technical contributions to the discussion of ICAO.
Thank you for your kind attention!
JAXA would like to express special thanks to Prof. Miyazawa, Prof. Katayanagi, Prof. Rinoie, Prof. Asai, Prof. Yonemoto, Prof. Yoneda for the D-SEND#2 flight test, and Prof. Obayashi, Prof. Matsushima, Prof. Takagi for the NEXST-1 design. And we greatly appreciate fruitful collaborations with ONERA, DLR, and NASA for supporting fundamental research activities.

Thank you for your kind attention!