TRAJECTORY DESIGN OF SILENT SUPERSONIC TECHNOLOGY DEMONSTRATOR (S3TD)

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Abstract

This paper presents an exploration of the possibility of a flight experiment for a small supersonic experimental aircraft by designing a flight trajectory. The guidance law was designed by combining an optimal ascent trajectory with minimum fuel consumption and a method to pass specified way points sequentially to accomplish an efficient flight experiment. Flight analyses were then performed. Although the results did not fully satisfy the mission requirements, technical issues and their solutions were explored. Refinements of the mathematical models and investigations of evaluation criteria and their values are necessary for the next design step.

1 Introduction

The Japan Aerospace Exploration Agency is designing a silent supersonic technology demonstrator (S3TD) to demonstrate design procedures to reduce sonic booms. This study investigates two points related to the S3TD. One is designing a flight trajectory that satisfies mission requirements. The other is finding technical subjects to perform flight experiment.

The mission requirements are summarized first herein. An optimal ascent flight trajectory with minimum fuel consumption will be designed; then flight experiments will be performed efficiently. A simple guidance law is designed and flight analyses are performed presuming the use of Evetts Airfield in Australia.

2 Design Conditions

2.1 Mission requirements

The mission requirements are presented in Table 1. The microphone arrays in line will be set on the ground to measure sonic booms. 'Above flight' in Table 1 means that the S3TD flies above the microphone arrays in the same direction; 'Across flight' means that the S3TD flies above the microphone arrays orthogonally. The target flight conditions for measuring the sonic boom are altitude 14 km and Mach number 1.6.

The optimal trajectory to satisfy the mission requirements of number 1 and 2 is designed to perform the flight experiments in this study.

2.2 Vehicle Configuration

The vehicle configuration and its specifications are shown in Fig. 1 and Table 2.

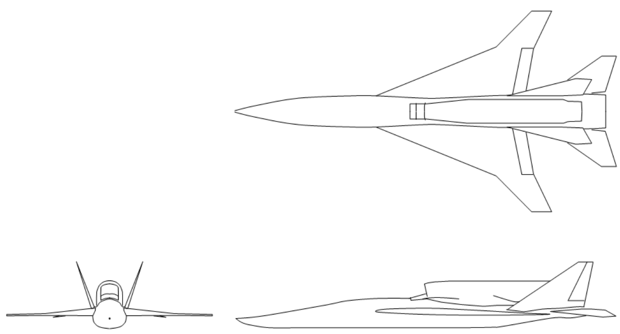

Fig. 1 Vehicle Configuration

Table 1 Mission Requirements

No.	Flight Name	Flight Direction	Objective
1	Reference flight (Above flight)	A*	Low-boom signature measurement
2	Reference flight (Across flight)	B*	Low-boom signature measurement (boom carpet distribution)
3	Opposite direction flight	A (opposite)	Robustness of low-boom signature for flight direction
4	Opposite direction flight	B (opposite)	Robustness of low-boom signature for flight direction (boom carpet)
5	Reference flight #2	A	Robustness of low-boom signature for atmospheric condition
6	Reference flight #2	B	Robustness of low-boom signature for atmospheric condition (boom carpet)
7	Low-drag flight	A	N-wave measurement for comparison
8	Low-drag flight	B	N-wave measurement for comparison (boom carpet distribution)
9	Mach variation flight	B	Robustness of low-boom signature for flight Mach number variation
10	Altitude variation flight	B	Robustness of low-boom signature for flight altitude variation
11	Focus-boom flight (acceleration)	A	Focus-boom measurement in acceleration flight
12	Focus-boom flight (pushover maneuver)	A	Focus-boom measurement in pushover maneuver
13	Focus-boom flight (cutoff Mach number)	A	Focus-boom measurement at cutoff Mach number
14	Focus-boom flight (turning maneuver)	A	Focus-boom measurement in turning maneuver
15	Focus-boom flight (carpet edge)	B	Focus-boom measurement at boom carpet edge

* ; A : Along microphone arrays   B : Across microphone arrays

Table.2 Vehicle Specifications

Item	Value	Unit
Reference Area	21	m^2
Gross Take-Off Weight	3500	kg
Dry Weight	2500	kg

The speed brake will be opened under Mach 0.45 during descent flight and will add 0.03 to the drag coefficient while maintaining the lift coefficient.

2.3 Aerodynamic Characteristics

The lift coefficient (CL) and drag coefficient (CD) are calculated respectively using the following equations.

$$CL = CL_{\alpha} \cdot \alpha \qquad (1)$$

$$CD = CDmin + K \cdot CL^2 \qquad (2)$$

Each coefficient is presented in Fig. 2-4.

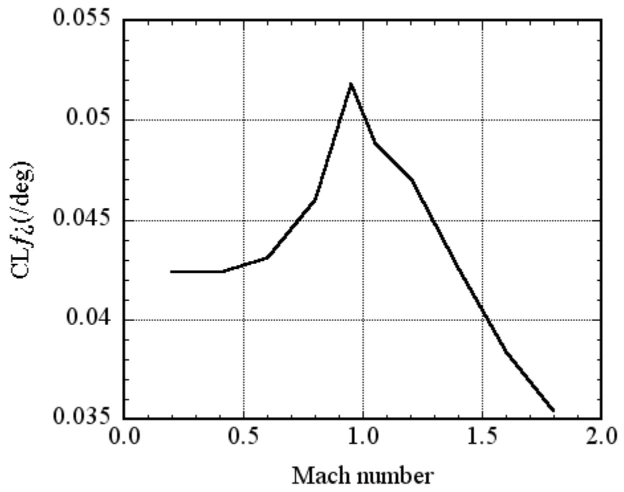

Fig. 2 CLα - Mach number

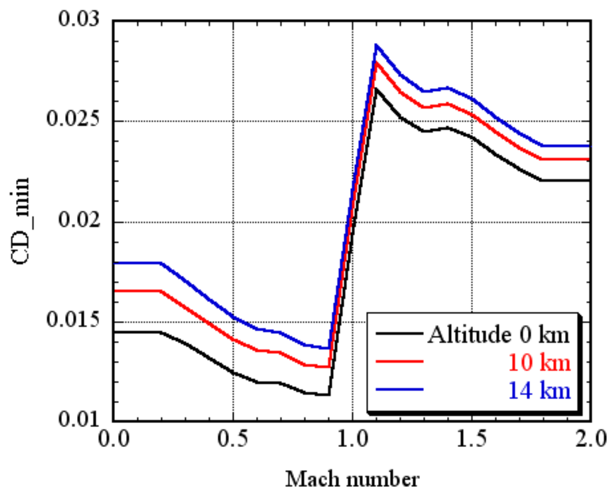

Fig. 3 CDmin - Mach number

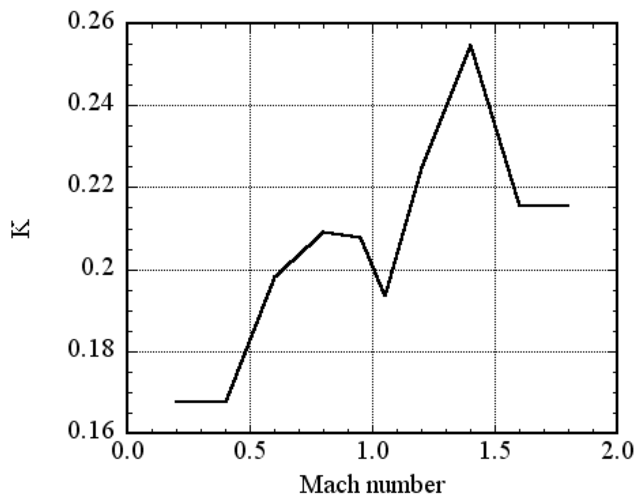

Fig.4 K - Mach number

2.4 Propulsion Characteristics

One F124 engine will be installed on the vehicle. The characteristics-net thrust and specific fuel consumption (SFC)-are portrayed respectively in Fig. 5 and Fig. 6.

3 Flight Trajectory Design

The flight trajectory design is described in this chapter. For this study, Evetts Airfield in Woomera is presumed as the runway. The microphone arrays set in line will be placed along the Range-Highway to measure the sonic boom (see Fig. 9) for easy setting and recovery. The length of straight segment of the Range-Highway is about 100 km. As a result of the ray path analysis, the sonic boom was estimated to reach 15 km ahead, and 30 km in a transverse direction to each side. The vehicle will proceed to 60 km above the microphone arrays first to satisfy the mission requirements. Then, the vehicle flies at right angles the middle point of the microphone line to measure the boom carpet. These flight patterns are the central segment of the flight trajectory. The segment from the starting point of sonic boom measurement to the end of measurement of the boom carpet is called the cruise phase herein.

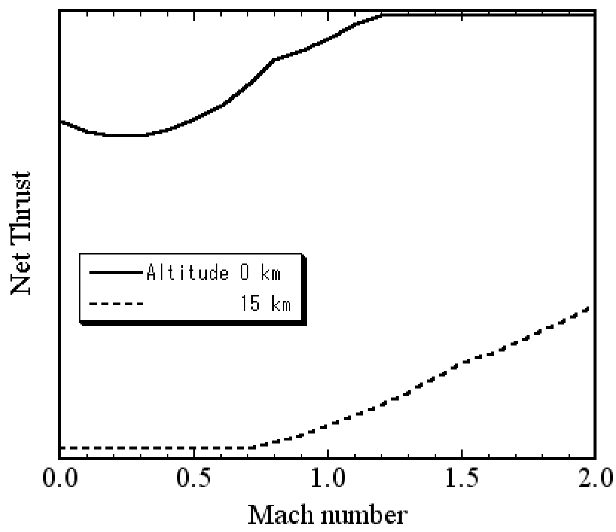

Fig. 5 Net-thrust-Mach number

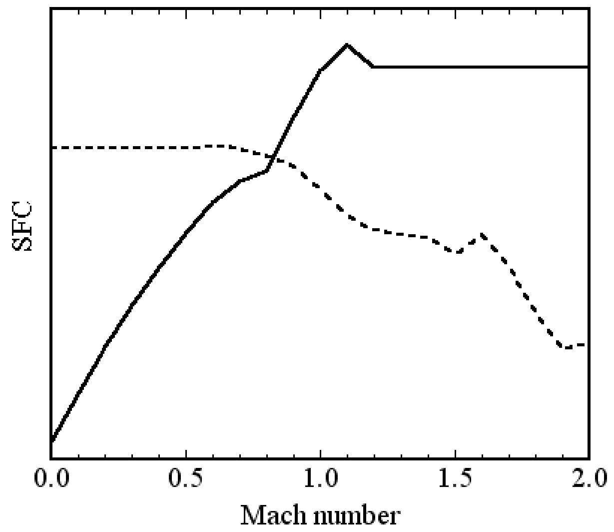

Fig. 6 SFC-Mach number

Results of pre-flight analyses clarified that the fuel is insufficient or barely sufficient to do a flight experiment satisfying the mission requirements without optimal design of the flight trajectory. Most fuel is consumed during ascent from taking off. An optimal trajectory with minimum fuel consumption from taking off to the starting point of sonic boom measurement is then designed. This flight phase is called the ascent phase.

The flight segment from the end of boom carpet measurement to touch-down at Evetts Airfield is called the return phase hirein. The S3TD vehicle must reduce the kinematic energy sufficiently in this phase so that the instrumental building (IB) can be located near Evetts Airfield.

Design of the optimal ascent trajectory is described in the next chapter. In Chapter 3.2, the guidance law will be described. The guidance law is designed using two algorithms: an algorithm for tracking of the optimal ascent trajectory during actual flight, and a method for passing the specified way points one by one.

3.1 Design of Optimal Ascent Trajectory

The ascent trajectory from taking off to the beginning of sonic boom measurement is designed to minimize fuel consumption. The optimal problem is formulated with state vector $\boldsymbol{x}$, control vector $\boldsymbol{u}$, and parameter vector π, and the minimizing index function J. The state vector is composed by altitude h, velocity V, path angle γ, azimuth angle ϕ, longitude η, latitude λ, and mass m. The control vector is composed by angle of attack α, bank angle σ, power lever angle CT. Furthermore, the parameter vector is flight time t_f. The index function is fuel consumption. The Sequential Conjugate-Gradient Restoration Algorithm (SCGRA) [1] is used to optimize the ascent trajectory. The initial condition is prescribed explicitly as the taking off condition; the final condition expresses the flight condition of sonic boom measurement. These are presented in Table 3.

The Earth is modeled as a non-rotating sphere. Equations of motion are not shown here.

The optimal ascent trajectory is portrayed in Fig. 7 and Fig. 8.

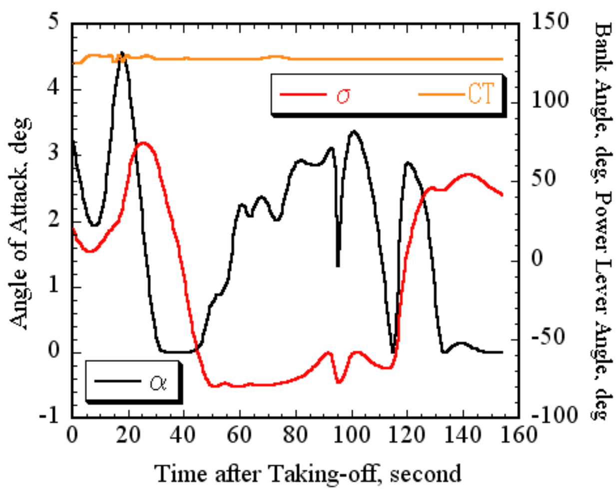

Fig. 7 Time Histories of Control Vector

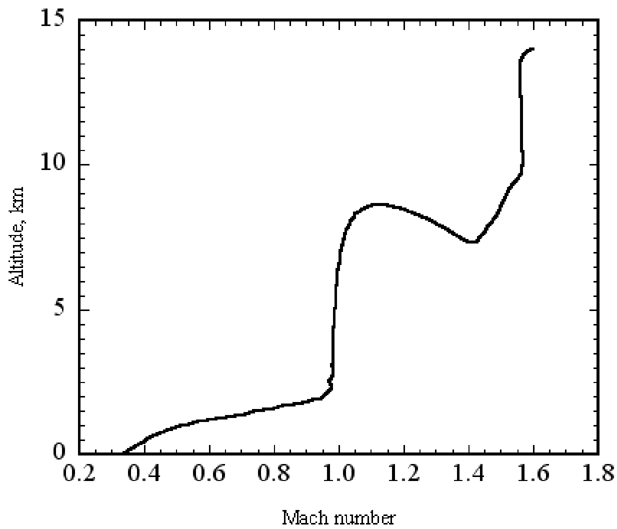

Fig. 8 Altitude-Mach number

Table 3 Initial and Final Conditions

Items	Initial (taking off)	Final (sonic boom measurement)
Latitude [°S]	30.987	30.830
Longitude [°E]	136.526	136.452
Altitude [km]	0.0	14.0
Velocity [m/s]	100.0	471.0 (Equal to Mach 1.6)
Path Angle [deg]	1.0	0.0
Azimuth Angle [deg]	356.0	301.5
Mass [kg]	3500.0	optimize

3.2 Guidance Law Design

The guidance law for the ascent phase is designed to follow the optimal ascent trajectory as a reference. The guidance law of the lateral direction for the cruise and return phase is designed for passing the specified way points one by one. The way points are portrayed in order in Fig. 10. Feedback gains are determined as follows. The response of the position error for the reference trajectory is modeled as a 2nd-order system first. The feedback gains are determined then by prescribing the natural frequency and damping ratio for each section. The guidance law of the longitudinal direction for the cruise phase is designed for maintaining the target altitude, 14 km, and the target Mach number, 1.6, by controlling the angle of attack and power lever angle. The longitudinal guidance law for the return phase has two modes. At the first mode, the vehicle descends at a low kinematical energy level with constant path angle to maintain the safety of the IB. The vehicle starts its range adjustment to Evetts Airfield in the second mode when the S3TD vehicle passes north of Evetts Airfield.

The nominal trajectory, presuming no error of the mathematical model, is depicted in Figs. 9, 10, and 11. The S3TD vehicle maintains a sufficient distance for accelerating to the target Mach number by turning east so that the distance from the Evetts Airfield to the beginning point of the sonic boom (way point 0) is very short. The 'above flight' is performed at the segment from way point 0 to way point 1. The S3TD vehicle turns to way point 4 to carry out the 'across flight'. Measurement of the sonic boom carpet is executed from way point 4 to way point 6. The sonic boom reaches the Range-Highway while the S3TD vehicle flies that section. Immediately after passing way point 6, the S3TD vehicle reduces flight velocity and altitude far away from IB for safety. Way points 6 and 7 are identical. The S3TD vehicle returns southbound to Evetts Airfield to avoid Woomera village, southeast of Evetts Aiefield. The S3TD vehicle controls velocity and altitude for landing from way point 8.

3.3 Flight Analysis

Table 4 shows error models of the mathematical model. Nominal steady wind and its error models are not formulated yet. The flight analysis is done as follows. The nominal flight simulation (presuming no error) is carried out first. The flight simulation, including only one error, is then performed and the flight simulations are carried out for error models of all types. The dispersions of evaluated items of error including simulation to the nominal simulation, called the root sum square (RSS), are calculated. For this study, fuel consumption and touch-down speed are chosen as evaluated items. Table 5 shows RSS values.

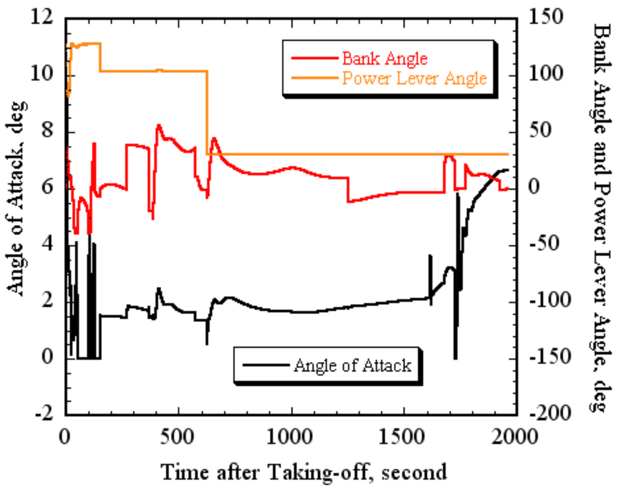

Fig.9 Time Histories of Control Vector

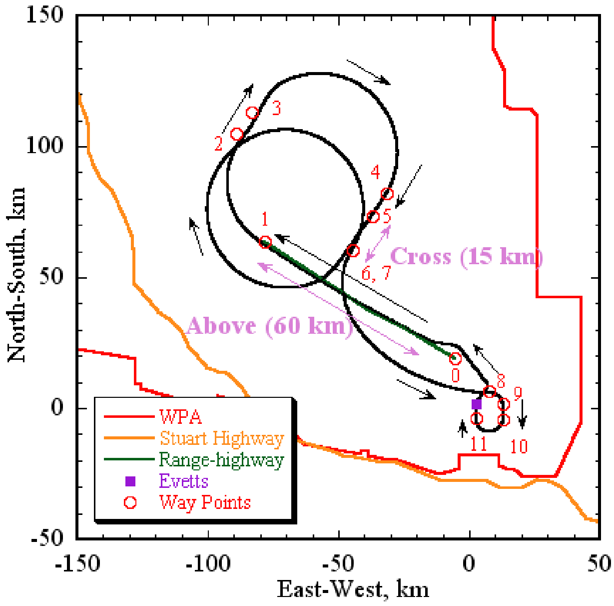

Fig. 10 Foot Print

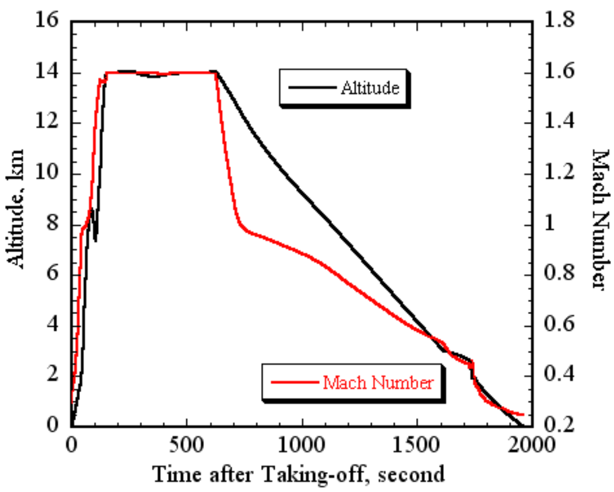

Fig. 11 Time Histories of Altitude and Mach Number

Table 4 Error Models

Items	Error Value
GTOW	±5%
CL, CD	±10%
Atmosphere Density	Based on U.S. 76
Thrust	±5%
SFC	±5%

Results confirmed that the mounted fuel is sufficient to perform the required flight experiment, taking into account the error of mathematical model. The touch-down speed slightly exceeded the restricted value. To reduce the touch-down speed is difficult using the present mathematical model because flight during the return phase is operated using minimum throttle and by opening the speed brake. The measures, changing gears to increase touch-down speed or extending the area of the speed brake, have a strong impact on cost, etc. Extending the flight time to reduce the touch-down speed using the remaining fuel and/or extending the landing gear to increase drag will be investigated in future studies. The precision of the mathematical model will also be refined.

Evaluation items not included in Table 5 are the required precision for target Mach number and altitude during sonic boom measurements. They are being investigated now from various perspectives based on ray path analysis. Limit values of the equilibrium air-speed and load factor are being investigated now. These limitations will be considered for flight analysis.

4 Conclusions

Results of flight analyses clarified that the installed fuel is sufficient to perform flight experiment. Although the touch-down speed is slightly greater than the restricted value, the knowledge drawn from results of flight analyses is reflected in the design and development of the demonstrator. Especially, requirements for a high reliable engine model and arrangement of the speed brake are important technical issues.

Table 5 RSS Values

Items	Nominal	RSS	SUM	Constraints
Fuel Consumption [kg]	840.3	141.9	982.2	Under 1000
Touch-down Speed [m/s]	68.2	13.8	82.0	Under 80

Reference

[1] A. K. Wu and A. Miele: Sequential Conjugate Gradient-Restoration Algorithm for Optimal Control Problems with Non-Difference Constraints and General Boundary Conditions, Part 1, *Optimal Control Applications & Methods*, Vol. 1, 1980, pp.69-88.

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