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T. Mori, M. Maita, and T. Tsuchiya
National Aerospace Laboratory of Japan
Tokyo, JAPAN

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Concept Study of Flying Test Bed for Hypersonic Airbreathing Engines

Takashige MORI*, Masataka MAITA*, and Takeshi TSUCHIYA*

Abstract

In Japan, National Aerospace Laboratory of Japan (NAL) has initiated to study the spaceplane concept and develop the required hypersonic technology bases since 1987.

The primary purpose of the spaceplane program is to provide technology as well as base research and development capabilities in critical disciplines for the future development of manned space transportation systems.

Hypersonic airbreathing propulsion systems that should be applied for future space transportation systems are urgent developmental subject. The realization of spaceplane systems is depending on airbreathing propulsion system performance.

Basic concepts of the Flying Test Bed (FTB) that are studied at the National Aerospace Laboratory (NAL) are unmanned, autonomously controlled, self-accelerating to hypersonic region and reusable vehicles. Hypersonic airbreathing test engines to be installed on the FTB have not yet confirmed its reliability during previous ground tests. Therefore, the FTB must maintain sufficient stability margin even in case of test engine's malfunction including sudden stop.

Two turbo-jet engines for take-off, fly-back cruse and landing and one rocket engine for accelerating to hypersonic region are installed in the FTB. Three propellants that are kerosene for jet engines and rocket engine fuel, liquid oxygen for rocket engine oxidizer and liquid hydrogen for test engine fuel are installed in the FTB fuselage. Kerosene tanks are separated into two tanks to control vehicle center of gravity by kerosene transfer. The FTB has a acceleration capability of up to flight MACH number of 6.

The FTB will horizontally take-off by jet engines, and accelerate to flight Mach number of 6 by a rocket engine. The FTB will turn to launch site direction without engine thrust and glide-back to launch site and horizontally land.

This paper describes the FTB system analysis results that include vehicle sizing analysis and flight analysis by NAL.

*1 National Aerospace Laboratory of Japan,
7-44-1 Jindaiji-Higashi, Chofu, Tokyo, 182-8522, Japan

I. Introduction

For the promotion of extended and diversified space activities, it is required to build the technology bases capable of supporting such space activities. Especially, the development of the low-cost space transportation systems to and from lower earth orbit, as driven by the clear need for affordability and operational flexibility, would be key issue.

For such advanced systems, the spaceplane integrated with a hypersonic airbreathing propulsion system, optimally configured as single stage to orbit, horizontal take-off and landing system, should be a potentially promising option. Hypersonic airbreathing propulsion systems that should be applied for future space transportation system are urgent developmental subject. The realization of a spaceplane system is depending on airbreathing propulsion system performance.

The Flying Test Bed (FTB) is a mandatory test vehicle for hypersonic airbreathing propulsion system developments to evaluate its flight performance, adaptability and reliability in the early development phase.

FTB flight test is necessary, because in-flight performance data cannot be obtained in static (non-accelerating) ground test facilities.

A spaceplane is basically an accelerator that reaches hypersonic flight speed within a few minutes after liftoff. Hypersonic airbreathing engines for future spaceplane system should operate under various speed conditions in one flight. And hypersonic airbreathing engines must be tested in the same flight condition as actual spaceplane in its early development phase.

The FTB should accelerate at the same acceleration rate as the actual spaceplane vehicle, and should fly wider flight conditions such as various flight dynamic pressures and flight Mach numbers, to obtain hypersonic airbreathing engine off-nominal performances. The FTB should achieve short turn around time operation and be robust in case of test engine malfunctions such as sudden stop. Horizontal take-off and land as well as flight-back capability are considered as mandatory requirements for the FTB.

II. FTB Concept

· Objectives

The objective of the FTB is to test hypersonic airbreathing engine performance in flight conditions. Target flight envelope of the FTB are up to flight Mach number of 6+ without test engine thrust and along with flight dynamic pressure of 50kPa that should be the upper limit in actual spaceplane operation.

· Fundamental Requirements

Fundamental requirements for the FTB are as follows.

(1) Flight testing for hypersonic airbreathing engines to be developed.

(2) Total of 20 ～ 30 flight test

(3) Fly back capability

(4) Unmanned fully autonomous operation

(5) Test airbreathing engine size of 8 meters in length and 80 centimeters in diameter

(6) Design and development by commercially available off-the-shelf technologies as possible.

(7) Horizontal powered take-off and landing with conventional jet engines.

(8) Acceleration by rocket engine from transonic region

· Vehicle Concept Image

The FTB vehicle main characteristics and weight estimation results are presented in Table 1 and 2. Figure 1 shows vehicle outline sketch and Figure 2 shows general views of the FTB vehicle. Fig 3 shows test hypersonic airbreathing engine image. Hypersonic airbreathing test engine will be installed under the body along with its vehicle centerline to realize cleaner intake airflow condition. Two conventional jet engines that are assumed as F100-PW-200 are installed at root section of wings. The jet engines are used during take-off, climbing, fly-back cruse and landing. Air intake for the jet engines will be closed during supersonic and hypersonic flight to prevent from aerodynamic heating. One rocket engine assumed as RD-120M is installed at aft end of the body and will be ignited at transonic flight in the air.

Kerosene is the common fuel for the jet engine and the rocket engine. The kerosene tanks are separated into two tanks to control vehicle center of gravity by kerosene transfer. LOX tank for rocket engine oxidizer is installed between two kerosene tanks. Liquid hydrogen tank for hypersonic test airbreathing engine is installed near its engine to make clear interface with test engines.

A vertical and horizontal tail system is selected to obtain sufficient stability even in case of test engine malfunction that include sudden stop.

III. Flight Trajectory Analysis

· Flight sequence

The FTB will take-off horizontally using jet engines from test site. The FTB will climb and accelerate to altitude of 10,000m and flight Mach number of 0.8. The rocket engine will start and accelerate the FTB to flight Mach number of 6. Fly-back maneuver will be initiated just after rocket engine cut-off. Pitch angle of attack and bank angle will be controlled to perform optimum fly-back trajectory to the launch site. The optimum fly-back trajectory is defined to achieve long-range flight in direction to launch site from its initial conditions.

·Flight Parameters

Flight parameters for a typical flight case that is acceleration to fight Mach number 6 along with flight dynamic pressure of 50kPa are presented in Table 3. Figure 4 shows flight profile of altitude vs. Mach number. Figure 5 shows Mach number history. The FTB will accelerate to Mach 6 within 483sec after take-off. Figure 6 shows dynamic pressure profile that is maintained at a constant value of 50kPa during rocket engine phase. Figure 7a and 7b show flight trajectory pattern reflecting to horizontal plane and vertical plane respectively. The FTB has fly-back capability to launch site without jet engine operation. The vehicle altitude at fly-back to launch site is 8,334m and flight speed is 126m/sec.

Figure 8a and 8b show pitch angle of attach history and bank angle history. Figure 9a and 9b show vehicle acceleration history along with vehicle centerline and vertical direction. Acceleration along with vehicle centerline is mainly caused by engine thrust of jet engine and rocket engine. The acceleration in vertical direction is caused by aerodynamic lift force that is maximized during fly-back maneuver relating with pitch angle of attack.

IV. Follow on R&D

The National Aerospace Laboratory of Japan will continue to study the FTB vehicle system for future reusable space transportation system development. CFD analysis should be conducted to provide aerodynamic forces and moments of the FTB vehicle before wind tunnel testing. Aerodynamic thermal heating environments around the vehicle should be examined to select a thermal protection system that will be selected from hot metal structure, ceramic tile, carbon-carbon composite and flexible thermal blanket. FTB concept without jet engines for take-off and return cruse operation should be studied to minimize vehicle size and weight.

Requirements for vehicle sub-systems such as structure, propulsion system, avionics, guidance and navigation, communication, data acquisition should be defined. The realization of the FTB concept should be confirmed in near future.

V. Concluding Remarks

Based on the present concept study of the FTB, main results that are mentioned below are obtained.

(1) The FTB has sufficient acceleration capabilities to test hypersonic airbreathing propulsion system for future transportation system.
(2) The FTB has fly-back capability to launch site without the jet engine operation.
(3) Eliminating jet engine system should reduce the FTB vehicle size and weight.
(4) The FTV has the possibility as flight test laboratory to evaluate aerodynamic phenomenon and high temperature materials in hypersonic flight region.

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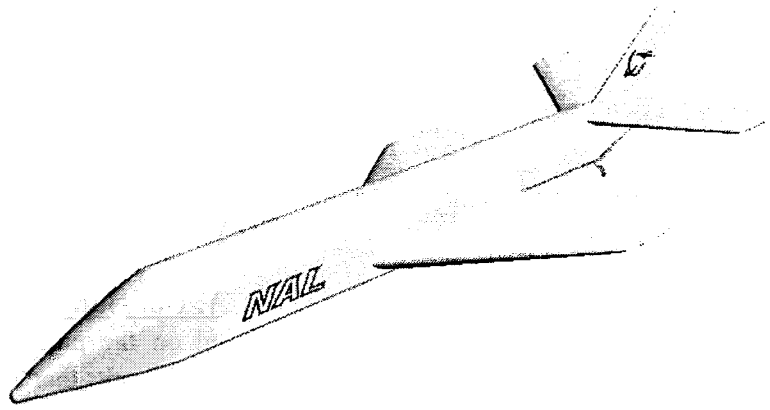

Fig.1 Vehicle Outline Sketch

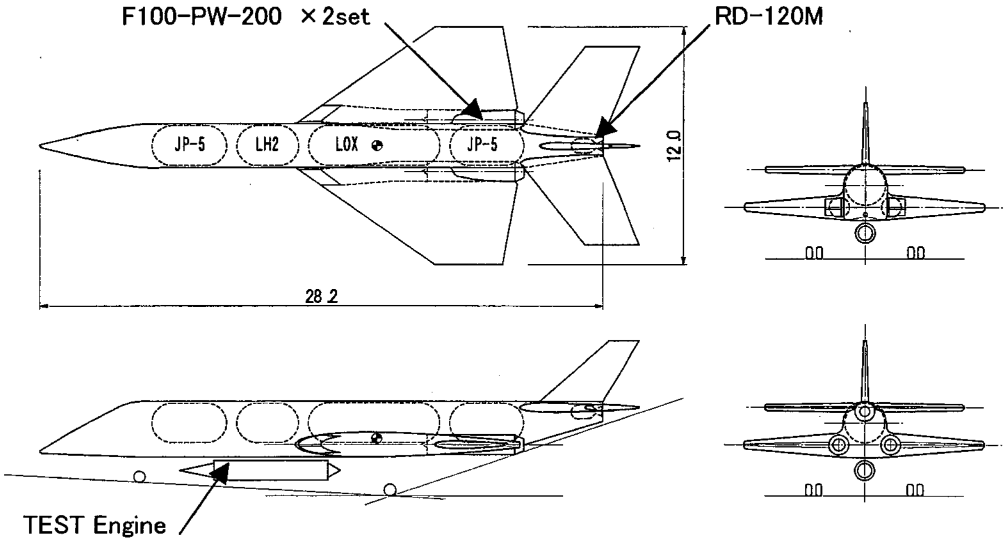

Fig.2 FTB Vehicle General View

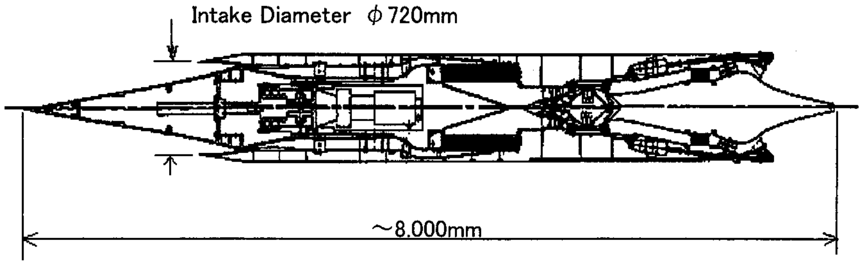

Fig.3 Test Engine Image

Table 1 FTB Characteristics

	Parameter	Unit	Value
1.	Take-off Weight	(kg)	50000
2.	Dry Weight (except Test Engine)	(kg)	14325
3.	Body		
3-1	Length	(m)	28.2
3-2	Diameter	(m φ)	2.2
4.	Wing		
4-1	Reference Area	(m²)	100
4-2	Span	(m)	12.016
4-3	Aspect Ratio	(-)	1.444
4-4	Leading Edge Sweepback Angle	(deg)	55
4-5	Trailing Edge Sweep Fwd. Angle	(deg)	10
4-6	Taper Ratio	(-)	0.26638
4-7	Mean Aerodynamic Chord	(m)	9.254
5.	Horizontal Tail Area	(m²)	28
6.	Vertical Tail Area	(m²)	7
7.	F100 Engine		
7-1	Max. Take-off Thrust	(kN)	100.53
7-2	Number of Engines	(-)	2
8.	RD120M Engine		
8-1	Expansion Ratio	(-)	4.96
8-2	Nozzle Exit Area	(m²)	0.14
8-3	Vacuum Thrust	(kN)	730.6
8-4	Mixture Ratio	(-)	2.72
8-5	Specific Impulse (vacuum)	(sec)	307
8-6	Throttling	(%)	-40~+3.5

Table 3 FTB Preliminary Flight Analyses

	Parameter	Unit	Value
1.	Take-off by F100 Jet Engine		
(1)	Vehicle Weight	(kg)	50,000
(2)	Relative Velocity	(m/s)	100.0
(3)	Pitch Angle of Attack	(deg)	18.88
(4)	Dynamic Pressure	(kPa)	6.1
2.	Start RD-120M Rocket Engine		
(1)	Time from Take-off	(sec)	375.31
(2)	Vehicle Weight	(kg)	43,310
(3)	Altitude	(m)	10,000
(4)	Relative Velocity	(m/s)	239.9
(5)	Mach Number	(-)	0.80
(6)	Flight Path Angle	(deg)	3.442
(7)	Dynamic Pressure	(kPa)	11.9
(8)	Down Range Distance	(km)	80.9
3.	Rocket Engine Burn out		
(1)	Time from Take-off	(sec)	482.95
(2)	Vehicle Weight	(kg)	17,168
(3)	Altitude	(m)	26,594
(4)	Relative Velocity	(m/s)	1,796.7
(5)	Mach Number	(-)	6.00
(6)	Flight Path Angle	(deg)	6.121
(7)	Dynamic Pressure	(kPa)	50.4
(8)	Down Range Distance	(km)	171.9
4.	Return Flight Phase before Approach & Landing		
(1)	Time from Take-off	(sec)	1,426.61
(2)	Vehicle Weight	(kg)	17,168
(3)	Altitude	(m)	8,334
(4)	Relative Velocity	(m/s)	126.3
(5)	Mach Number	(-)	0.41
(6)	Flight Path Angle	(deg)	-6.654
(7)	Dynamic Pressure	(kPa)	4.0
(8)	Down Range Distance	(km)	0

Table 2 FTB Weight Estimation

	Parameter	Weight(kg)	
1.	Body	2,613	
2.	Wing	1,568	
3.	Horizontal Stabilizer	626	
4.	Vertical Stabilizer	252	
5.	Landing Gear	1,932	
6.	Thermal Protection	503	
7.	Engines	4,562	
7-1	F-100 Engines		2,894
7-2	F-100 Engines Thrust Str.		197
7-3	RD120M Engine		1,285
7-4	RD120M Engine Thrust Str.		186
8.	Tanks	706	
8-1	LOX Tank		407
8-2	Kerosene Tank Fwd		113
8-3	Kerosene Tank Aft		113
8-4	LH2 Tank		73
9.	Hydraulic	159	
10.	Plumbing	489	
11.	Avionics, Electronics	1,100	
12.	Test Engine System	1,000	
	Dry Weight	15,398	
13.	Propellants	34,518	
13-1	LOX		19,130
13-2	Kerosene Fwd		7,457
13-3	Kerosene Aft		7,457
13-4	LH2		474
14.	Margin	84	
	Take-off Weight	50,000	

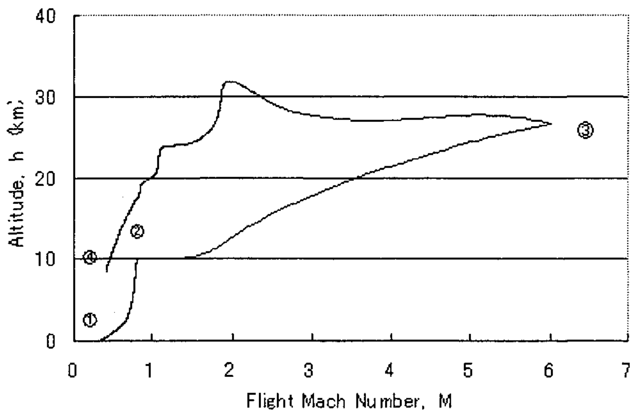

Fig.4 Flight Profile

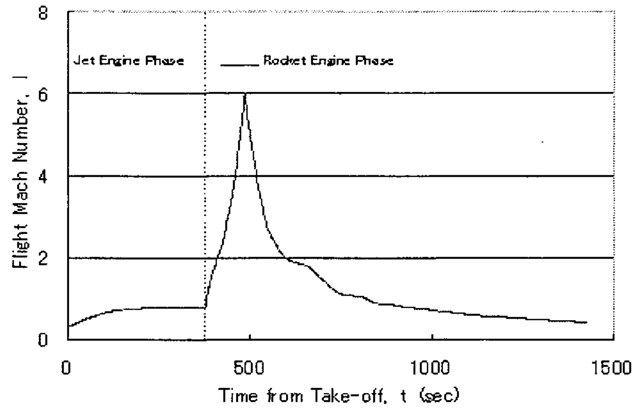

Fig.5 Flight Mach Number

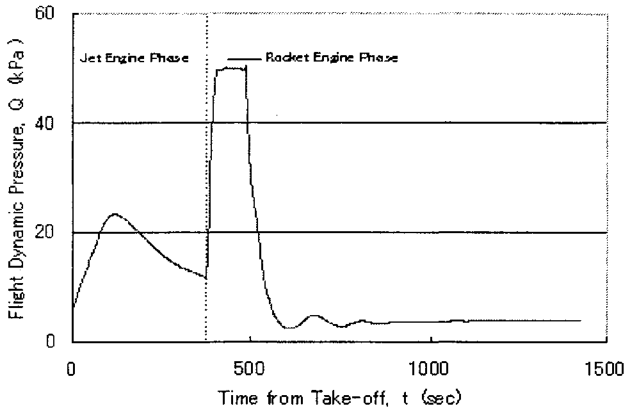

Fig.6 Flight Dynamic Pressure

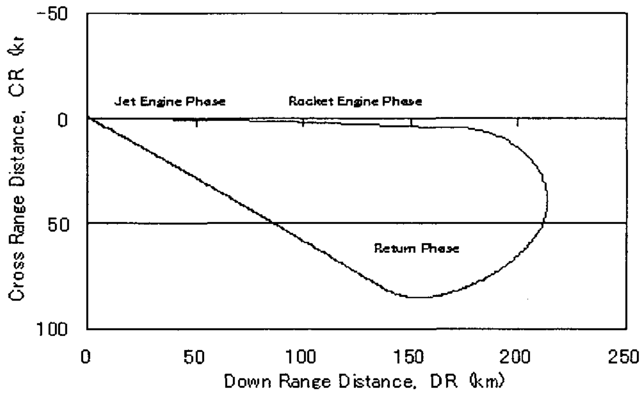

Fig.7a Cross Range Distance VS. Down Range Distance

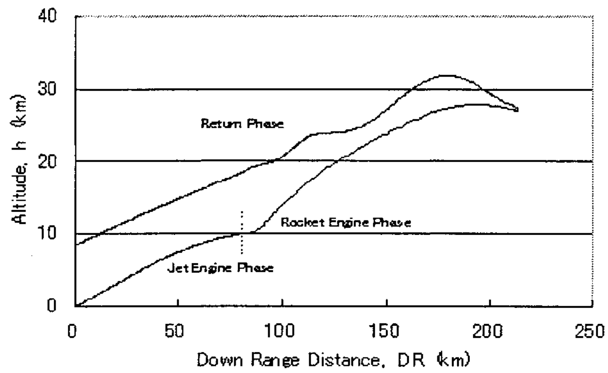

Fig.7b Altitude VS. Down Range Distance

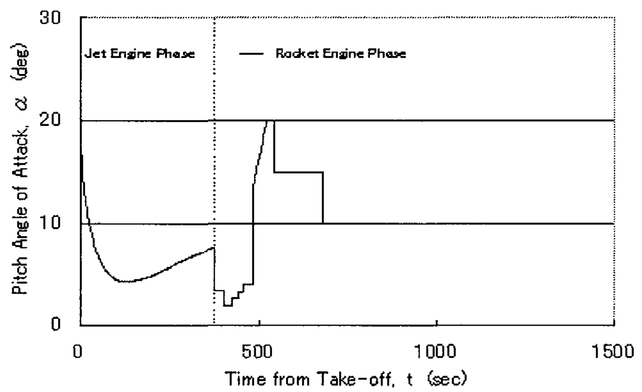

Fig.8a Pitch Angle of Attack

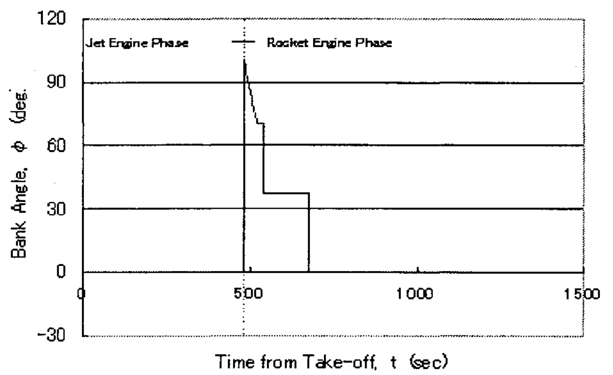

Fig.8b Bank Angle

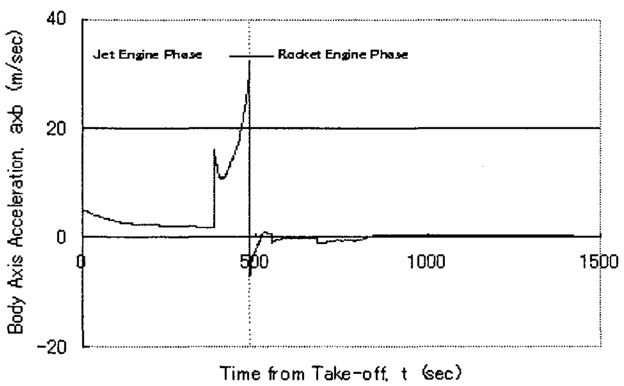

Fig.9a Body Axis Acceleration

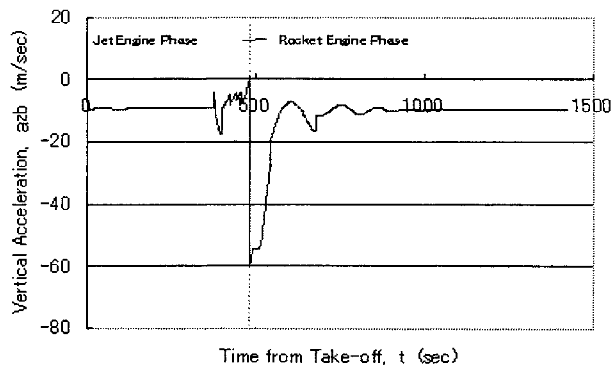

Fig.9b Vertical Acceleration