DEVELOPMENT OF A SMALL-SCALE SUPERSONIC FLIGHT EXPERIMENT VEHICLE AS A FLYING TEST BED

Kazuhide Mizobata, Ryojiro Minato, Ken Higuchi, Masazumi Ueba, Syohei Takagi, Daisuke Nakata, Nobuhisa Katsumata, Kazuyuki Higashino, and Nobuhiro Tanatsugu
Aerospace Plane Research Center (APReC), Muroran Institute of Technology, Japan
e-mail: mizobata@mmm.muroran-it.ac.jp

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Abstract

Innovation in technologies for high-speed atmospheric flights is essential for establishment of both supersonic/hypersonic and reusable space transportations. It is quite effective to verify such technologies through small-scale flight tests in practical high-speed environments, prior to installation to large-scale vehicles. Thus we are developing a small-scale supersonic flight experiment vehicle as a flying test bed. Two generations of aerodynamic configuration with a cranked-arrow main wing are proposed. Concerning their propulsion system, twin counter-rotating axial fan turbojet (CRAFT) engines are proposed for the 1st generation, whereas an air-turbo ramjet gas-generator cycle (ATR-GG) engine is proposed for the 2nd generation. Their aerodynamics are analyzed intensively through wind tunnel tests and are found to be favorable. On the basis of the aerodynamic characterization and propulsion design analysis, flight capability is predicted to be appropriate for realization of supersonic flights up to Mach 2. Prior to the construction of the supersonic vehicles, a full scale prototype vehicle and subscale vehicles are designed and fabricated in order to verify the subsonic flying characteristics through flight tests. Preliminary flight tests of the 1st-generation prototype vehicle are carried out and good flight capability in subsonic regime is demonstrated. Development of the engine, airframe structure, and autonomous guidance/control system is underway. This prospective flight experiment vehicle will be applied to flight verification of innovative fundamental technologies for high-speed atmospheric flights such as turbo-ramjet propulsion with endothermic or biomass fuels, MEMS and morphing techniques for aerodynamic control, aero-servo-elastic technologies, etc.

Nomenclature and Abbreviations

AADP	:	aileron alone departure parameter
AOA	:	angle of attack
b	:	wing span
C_D	:	drag coefficient
C_L	:	lift coefficient
C_l	:	rolling moment coefficient
C_m	:	pitching moment coefficient
C_n	:	yawing moment coefficient
I	:	moment-of-inertia matrix
L	:	rolling moment
LCDP	:	lateral control departure parameter
M	:	flight or flow Mach number or pitching moment
MAC	:	mean aerodynamic chord
$\vec{M}_b$	:	aerodynamic moments vector with respect to the body-fixed coordinates
N	:	yawing moment
α	:	angle of attack
β	:	side slip angle
δ_e	:	deflection angle of elevator
δ_a	:	deflection angle of aileron
δ_r	:	deflection angle of rudder
$\vec{\Omega}_b$	:	angular velocity vector with respect to the body-fixed coordinates

1. Introduction

Innovation in technologies for high-speed atmospheric flights is essential for establishment of supersonic/hypersonic and reusable space transportations. It is quite effective to verify such technologies through small-scale flight tests in practical high-speed environments prior to installation to large-scale vehicles. Thus we are developing a small-scale supersonic flight experiment vehicle as a flying test bed. This paper outlines such development efforts with emphasis on aerodynamic configuration designs and characterization through wind tunnel tests and flight capability predictions.

We propose two generations of aerodynamic configuration with a cranked-arrow main wing. In the 1st generation, twin counter-rotating axial fan turbojet (CRAFT) engines are proposed for propulsion, whereas an air-turbo ramjet gas-generator cycle (ATR-GG) engine is proposed for the 2nd generation. The aerodynamic stability and controllability of the configurations are analyzed in detail through wind tunnel tests. These treatments and results will be elaborated in Section 2. On the other hand, the concepts of the proposed CRAFT and ATR-GG engines will be outlined briefly in Section 3. On the basis of the aerodynamic characterization and propulsion design analysis, flight capability predictions are carried out. It will be described in Section 4. Section 5 describes a trial for drag reduction in the transonic regime by the area rule. Prior to the construction of the supersonic vehicles, a full scale prototype vehicle and subscale vehicles are designed and fabricated in order to verify the subsonic flying characteristics through flight tests. Section 6 will outline such efforts. Then Section 7 is conclusions.

2. Configuration Designs and Aerodynamic Characterization

2.l Proposed Configuration Designs

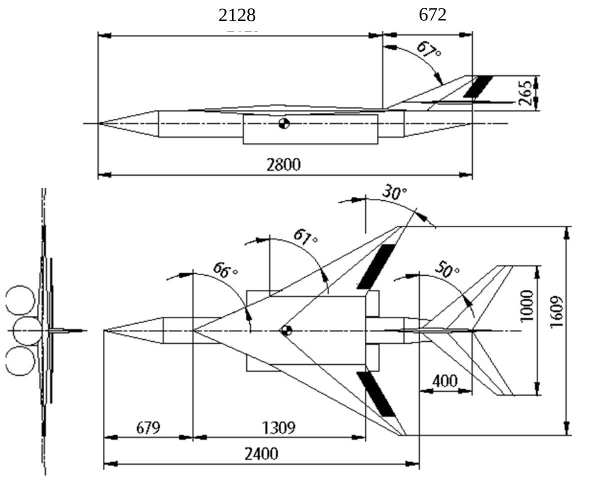
The twin engine configuration M2006 shown in Fig. 1 was proposed as the baseline configuration for the 1st-generation vehicle at the beginning of the development project. It has ailerons, a rudder, and all-pivoting horizontal tails as control surfaces. Its main wing has a cranked-arrow planform with large sweepback angles of 66 degrees on the inboard portion and 61 degrees on the outboard portion. Such planform is expected to attain stable aerodynamics in subsonic regime as well as reduction in wave drag in transonic and supersonic regime. The wing section for its main wing and tails is a diamond with 6 % thickness for reduction of profile wave drag.

In addition, a modified configuration M2006prototype was proposed for construction of a prototype vehicle, in which the following modifications were applied as shown in Fig. 1 (b):

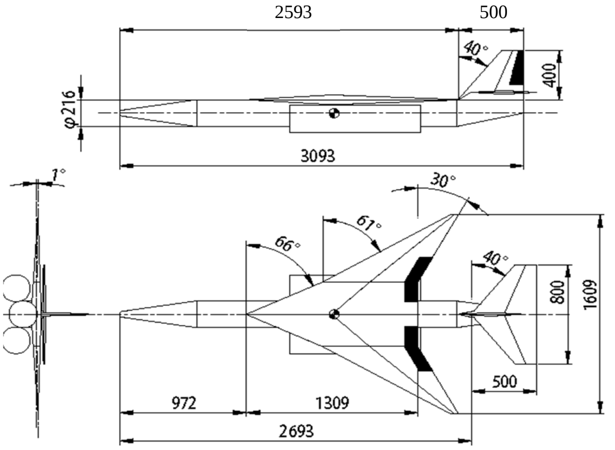
(a) Its horizontal and vertical tails are enlarged and less swept-back for enhancement of stability and controllability during takeoff and landing.
(b) Its lateral control capability is enhanced by adopting all-pivoting elevons.
(c) A pair of inboard flaps is installed for takeoff and landing.
(d) Its engine nacelles are connected to the fuselage on its both sides for the sake of convenience in fabrication and maintenance.
(e) Its nose is extended forward in order to attain sufficient capacity for installing fuel and avionics in the fuselage.

Furthermore, a revised configuration M2011 with a single ATR-GG engine was designed for the 2nd-generation vehicle as shown in Fig. 1 (c). Its wing and tail geometries are rigorously similar to those in the configuration M2006prototype. Its wingspan and fuselage diameter are enlarged by a factor of 1.5 so as to install the ATR-GG engine with a diameter of 230mm and to retain the ratio of wingspan to fuselage diameter. Three types of noses, A, B, and C with fuselage length of 5.8m, 6.8m, and 7.8m, respectively, are adopted for various quantities of propellants loaded as listed in table 1. In addition, three types of air-intake length are assumed so as to allow uncertainty in intake design.

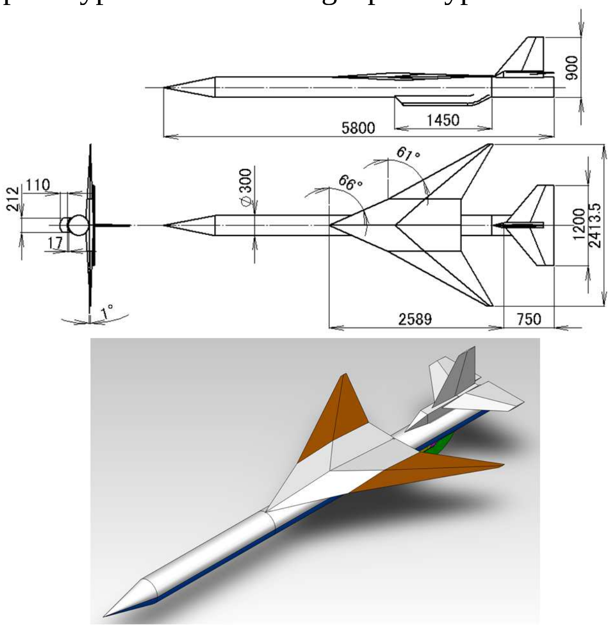
Because of the similarity between these three configurations, most of their aerodynamic characteristics are expected to be equivalent. The results of the series of wind tunnel tests will be outlined in the following subsections.



(a) The initial configuration M2006 with all-pivoting horizontal tails for the first generation vehicle.



(b) The modified configuration M2006-prototype for constructing a prototype vehicle.



(c) The proposed revision configuration M2011 for the 2nd-generation vehicle.

Fig. 1. Proposed aerodynamic configurations.

Table 1. Dimensions of the configurations M2006prototype and M2011

	M2006-prototype	M2011
Wing Span [mm]	1609.0	2413.5
Wing Area [mm2]	954856.8	2148427.8
Fuselage Diameter [mm]	200	300
Overall Length [mm]	3192	Nose-A: 5800 Propellant 80kg
		Nose-B: 6800 Propellant 105kg
		Nose-C: 7800 Propellant 130kg

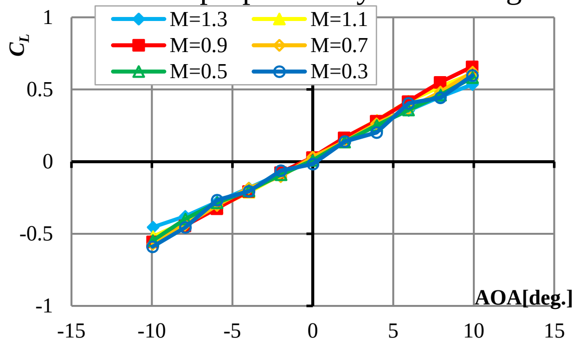
2.2 Lift and Drag Characteristics

The Comprehensive High-speed Flow Test Facility at the Institute of Space and Astronautical Science (ISAS) of the Japan Aerospace Exploration Agency (JAXA) and a Goettingen-type subsonic wind-tunnel at Osaka Prefecture University are used for the aerodynamic characterization. The results for lift and drag of the 1st-generation configurations M2006 and M2006prototype are as follows [1]:

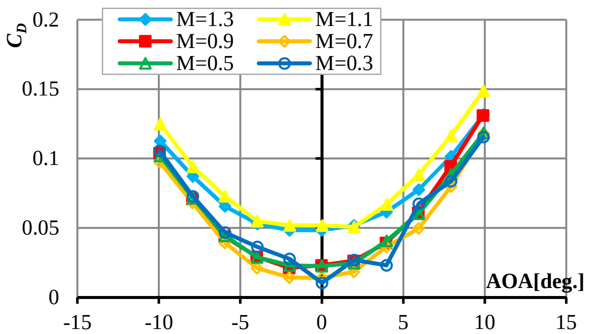
- ✓ The lift coefficient curves for show quite a good linearity with a slope of 0.058/deg. for subsonic, 0.065/deg. for transonic, and 0.043/deg. for supersonic regime, where the elevators are fixed.
- ✓ The so-called sound barrier, i.e. the drag peak at transonic regime, is small owing to the large sweep-back angles of the wing and tails.
- ✓ The linearity of the lift coefficient is found to be good for positive AOA up to 30 degrees, owing to the stability of the vortex system over the present cranked-arrow wing with a large inboard sweepback angle of 66 degrees as mentioned in the literature [2]. The linearity deteriorates for negative AOA probably because the engine nacelles would interfere with the vortex system.

The longitudinal aerodynamics of the 2nd-generation configuration M2011 were also measured by wind-tunnel tests as shown in Fig.

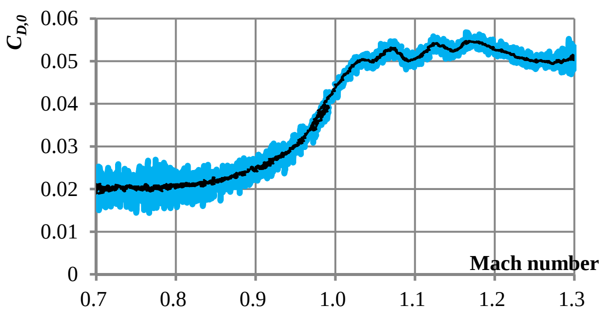
2. Its lift characteristics are quite similar to those for M2006 and M2006prototype, whereas the drag coefficient is reduced because of modification in propulsion system configuration.



(a) Lift coefficient.



(b) Drag coefficient.



(c) Mach number dependence of the zero-lift drag coefficient.

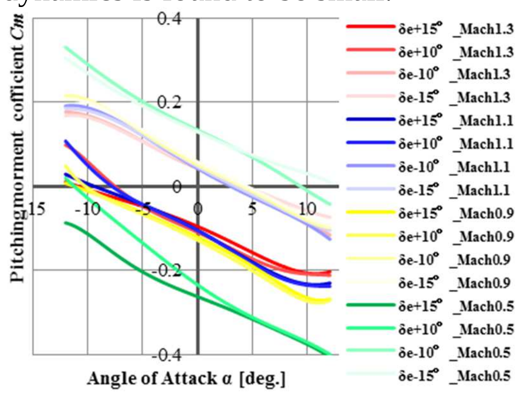
Fig. 2. Lift and drag characteristics of the 2nd-genertion configuration M2011 measured by wind tunnel tests.

2.3 Trim Capability, Stability, and Controllability for Attitude Motion

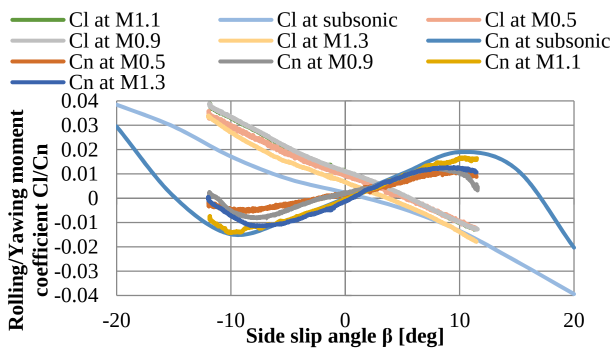
The measured variation of the pitching, rolling, and yawing moment coefficients of the 1st-generation configurations M2006 and M2006prototype with and without control surface deflections were quite appropriate [1]. Quite similar and adequate moment characteristics of the 2nd-generation configuration M2011 are confirmed by wind tunnel tests as shown in Fig. 3 for all Mach numbers ranging from 0.1 to 1.3.

2.4 Influence of the Nose and Intake Lengths of the Configuration 2011

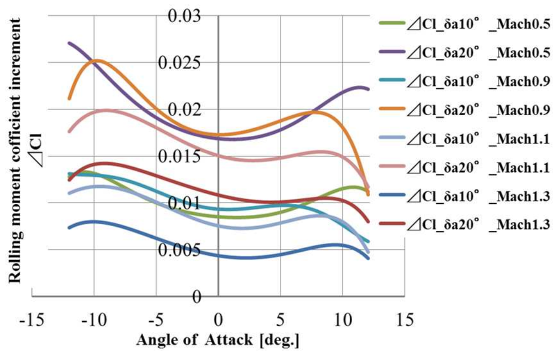
Lift, drag, and pitching moment coefficients are measured for several sets of nose and intake lengths in the configuration M2011, and are illustrated in Fig. 4. The influence of the nose and intake lengths on the longitudinal aerodynamics is found to be small.



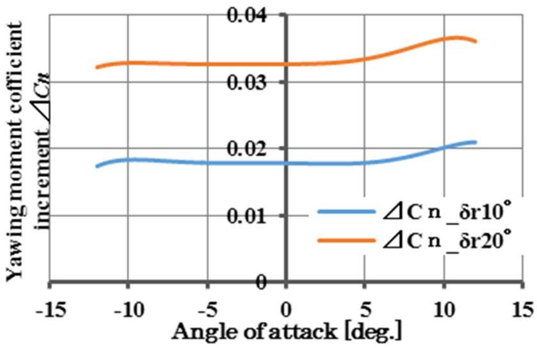
(a) Pitching moment coefficient for several elevator deflections.



(b) Rolling and yawing moment coefficients vs. sideslip angle.



(c) Rolling moment coefficient for some aileron deflections.



(d) Yawing moment caused by rudder deflections.

Fig. 3. Aerodynamic moment coefficients around the aerodynamic center (25%MAC) for the 2nd-generation configuration M2011 measured by wind tunnel tests.

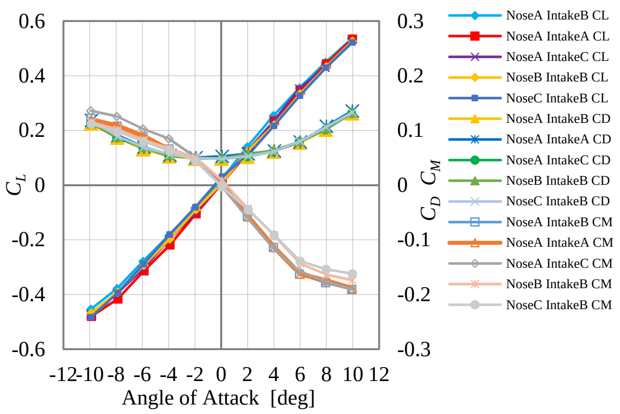


Fig. 4. Lift, drag, and pitching moment coefficients at Mach 1.3 for several sets of nose and intake lengths in the 2nd-generation configuration M2011.

2.5 Lateral Control Departure Characteristics

The roll control capability by aileron deflection may deteriorate at high angles of attack typically on taking-off and landing, owing to dihedral and adverse yaw effects. Such characteristics are assessed by the so-called aileron alone departure parameter (AADP) [3]:

$$\mathrm{AADP} = C_{n,\beta} - \frac{C_{n,\delta_a}}{C_{l,\delta_a}} C_{l,\beta} \qquad (1)$$

and the lateral control departure parameter (LCDP) when simultaneous rudder deflection is applied:

$$\mathrm{LCDP} = C_{n,\beta} - \frac{C_{n,\delta_a} + kC_{n,\delta_r}}{C_{l,\delta_a} + kC_{l,\delta_r}} C_{l,\beta} \qquad (2)$$

where $k = {}^{\delta_r}/_{\delta_a}$ is the rudder gain. The negative values of LCDP/AADP indicate negative aileron effectiveness i.e. roll reversal. Fig. 5 shows the evaluated LCDP/AADP for the configurations M2006prototype and M2011 with a nose-C on the basis of subsonic wind-tunnel tests. The M2006prptotype has a positive roll capability for AOA up to 19 degrees, whereas the M2011nose-C has negative roll characteristics at AOA above 12 degrees which takes place easily on taking-off and landing. Such roll reversal is caused by the reduction in directional stability $C_{n,\beta}$ due to the large nose length and by adverse yaw and large dihedral effects in the M2011 configuration. In order to prevent this roll reversal, coordinating the rudder deflection with the ailerons so as to enhance directional stability is quite effective as shown by the red curve with k = 1.0 in Fig. 5.

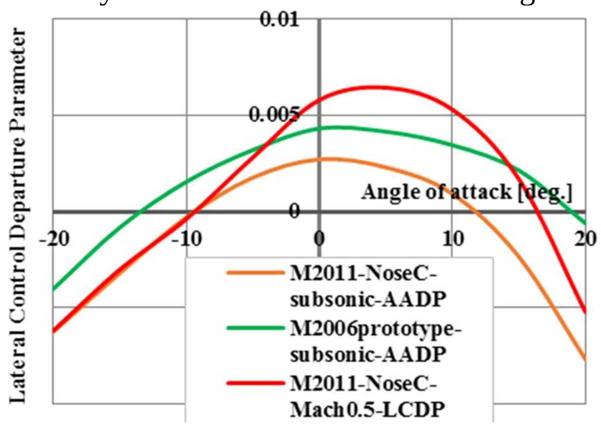


Fig. 5. Evaluated LCDP/AADP for the configurations M2006-prototype and M2011 with a nose-C on the basis of wind-tunnel tests.

3 Concept and Design of the Proposed Engine

3.1 A counter-rotating axial fan turbojet (CRAFT) engine for the 1st-generation vehicle

A counter-rotating axial fan turbojet (CRAFT) engine was proposed and designed for installation onto the proposed 1st-generation flight experiment vehicle [4]. In this engine the rotor fans in the first and the second stages rotate in an opposite direction and the stator fans can be eliminated to establish a compactness of the engine configuration. A prototype engine was fabricated and is undergoing ground tests as shown in Fig. 6.

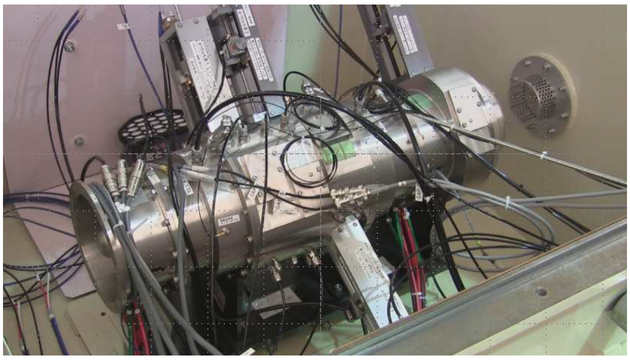
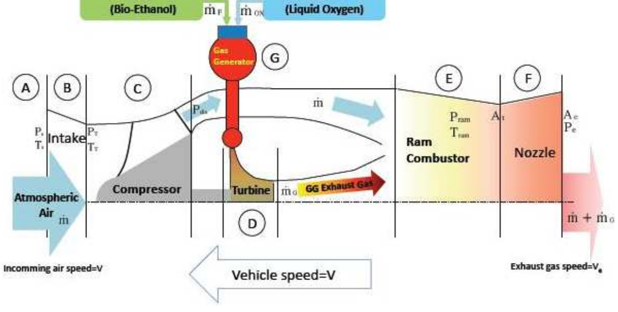


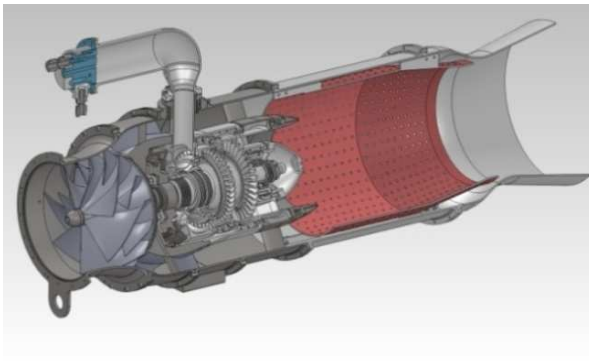
Fig. 6. The fabricated prototype counter-rotating axial fan turbojet (CRAFT) engine for ground tests.

3.2 An air-turbo ramjet gas-generator cycle (ATR-GG) engine for the 2nd-generation vehicle

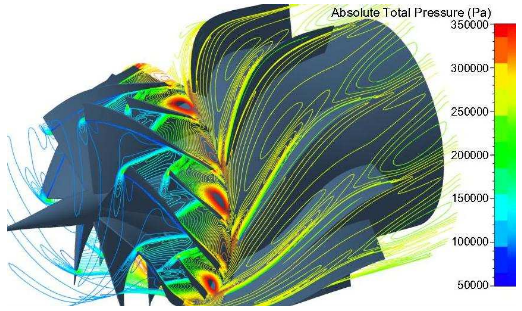
An air-turbo ramjet gas-generator cycle (ATR-GG) engine was designed for improvement in thrust at supersonic flights [5]. Its conceptual schematic is shown in Fig. 7 (a). Its turbine inlet condition is independent of the flight condition since the turbine is driven by the gas generator. Thus this type of engine is quite suitable to supersonic flights. The thrust and specific impulse of the proposed engine are rated at 3.8kN and 570sec respectively at a sea-level static condition, and 2.3kN and 720sec respectively at an altitude of 17km and Mach 2.0 (dynamic pressure 25kPa). The 3-D view of the proposed design is illustrated in Fig. 7 (b). Compressor fans and turbine bliscs were designed using the turbo-machinery design software AxCent and their fluid-dynamics were analyzed using the turbo-machinery analysis software FineTURBO as shown in Fig. 7 (c). A prototype engine has been fabricated as shown in Fig. 7 (d). It is to be applied to ground tests in this and next year.



(a) A conceptual schematic.



(b) 3-D view of the engine design.



(c) CFD analysis of the compressor fans.

(d) A fabricated prototype engine for ground tests.

Fig. 7. The proposed ATR-GG engine.

4 Flight Capability Prediction

Flight capability of the proposed 1st-generation vehicle was predicted by point mass analysis on the basis of the lift and drag characteristics measured by wind tunnel tests, thrust and specific impulse evaluations of the proposed engine, and a preliminary weight estimation of the airframe [1]. It was found that the vehicle can attain supersonic flight at Mach 1.6 for about one minute and a sufficient endurance for return flight. The upper limit in flight Mach number is correspondent to that in the turbine inlet temperature of the proposed CRAFT engine. This constraint can be eliminated in the ATR-GG engine to be installed on the 2nd-generation vehicle.

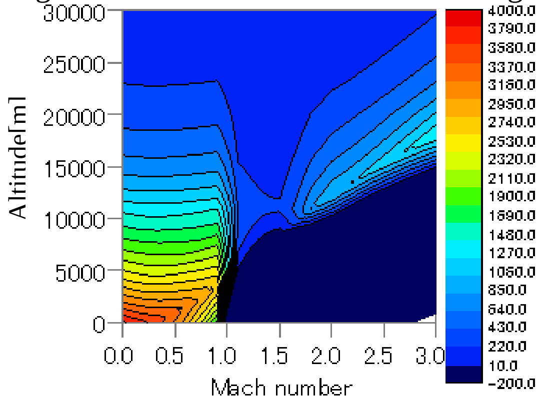
The thrust margin, i.e. thrust minus zero-lift drag, was evaluated for the proposed 2nd-generation vehicle with the aerodynamic configuration M2011 and an ATR-GG engine on the basis of the wind-tunnel tests and the engine design analysis. The results are illustrated in Fig. 8 with respect to flight Mach number and altitude. A narrow corridor is shown in the transonic region and a saddle point exists at about Mach 1.3 and 11km altitude. The vehicle must fly through this saddle point and the corridor in order to reach supersonic region.

Flight trajectory analysis of three degrees of freedom, i.e. point mass analysis was carried out for several conditions on the engine rotation, the loaded propellant mass, and the reduction in drag and structural weight. One of the results is shown in Fig. 9, where an engine rotation of 105% and a loaded propellant of 130kg (correspondent to the Nose-C and a fuselage length of 7.8m) were assumed. This result indicates that some enhancement in thrust and/or reduction in drag are required for a flight capability to reach Mach 2.0.

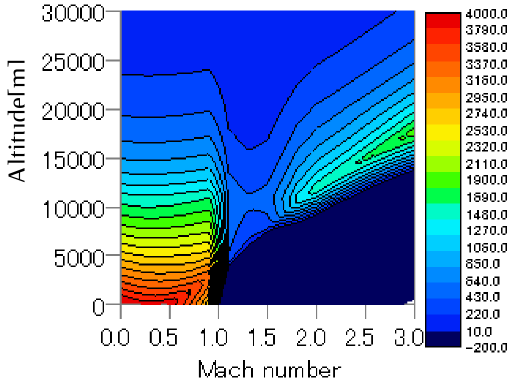
In addition, a six-degree-of-freedom flight simulation system is being constructed on the basis of the following equations of attitude motion [6]:

$$\vec{M}_b = \begin{bmatrix} L \\ M \\ N \end{bmatrix} = I\dot{\vec{\Omega}}_b + \vec{\Omega}_b \times (I\vec{\Omega}_b) \qquad (3)$$

where $\vec{M}_b = [L, M, N]^T$ is the aerodynamic moments with respect to the body-fixed coordinates, I is the moment-of-inertia matrix, and $\vec{\Omega}_b$ is the angular velocity vector with respect to the body-fixed coordinates. An analysis code is composed using the MATLAB/Simulink [7] and flights of the 2nd-generation vehicle with the configuration M2011 Nose-A were solved. Their results illustrated partly in Fig. 10 show that the vehicle will take off from the Taiki Flight Experiment Airfield after running 400 meters for about 10 seconds on the runway. It makes a round flight with a maximum altitude of 11km and a maximum Mach number of 1.15. Its downrange is 45km and the flight duration is 550 seconds. This flight trajectory is a subset of that of the configuration M2011 Nose-C shown in Fig. 9.

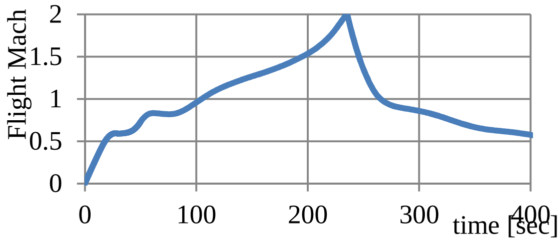


(a) Nominal rotation of the engine.

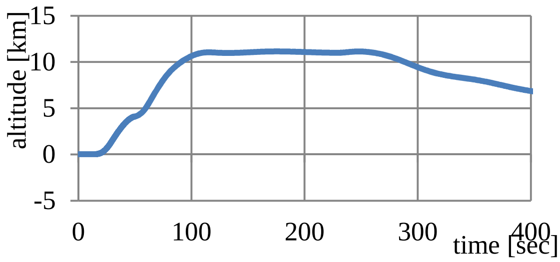


(b) 105% rotation of the engine.

Fig. 8. Evaluated thrust margin [N] for the 2nd-generation vehicle with one ATR-GG engine.

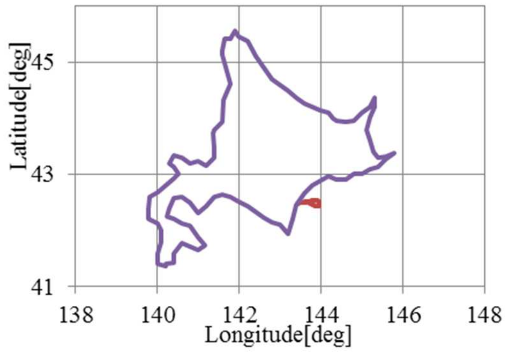


(a) History of the flight Mach number.

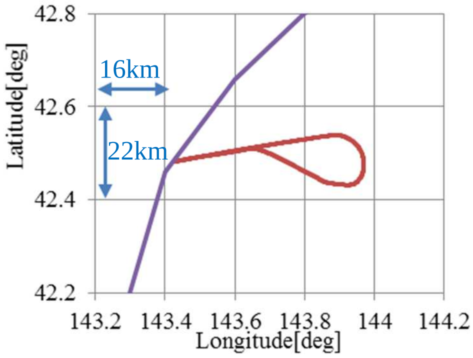


(b) History of the flight altitude.

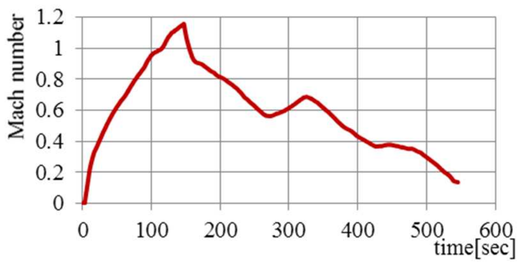
Fig. 9. Results of the three-degree-of-freedom flight analysis for the 2nd-generation vehicle with a Nose-C, i.e. loaded propellant of 130kg. An engine rotation of 105% are also assumed.



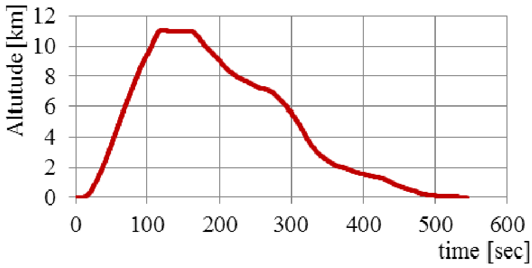
(a) Flight trajectory.



(b) Zoomed flight trajectory.



(c) History of the flight Mach number.



(d) History of the flight altitude.

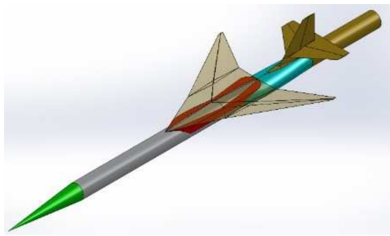
Fig. 10. Results of the six-degree-of-freedom flight analysis for the 2nd-generation vehicle with a Nose-A.

5. Drag Reduction in Transonic Regime

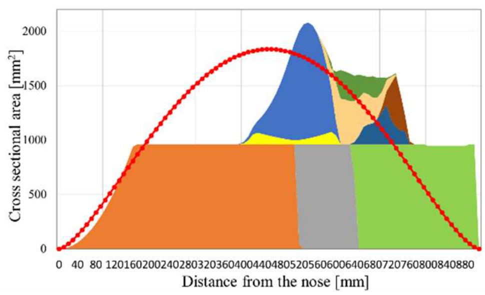
As indicated in the thrust margin and flight trajectory analyses, some reduction in transonic drag is required for a sufficient flight capability to reach Mach 2.0. Such reduction can be attained by modification of the aerodynamic configuration on the basis of the so-called area-rule, so as to make the cross sectional area distribution close to the Sears-Haack curve. Fig. 11 shows a trial modification composed of the following elements:

1. sharpening the nose
2. moving the wings and tails forward
3. adding a pair of bulges on the fuselage between the main wing and the tails

The results of a wind-tunnel test and wave-drag analysis for a modification with the above elements 1 and 3 are illustrated in Fig. 12 and show 5 to 20 % drag reduction in the transonic regime. More detailed tests and analysis are to be carried out.



(a) Overall appearance.



(d) The cross-sectional area distribution.

Fig. 11. The configuration M2011 Nose-C modified by the area rule.

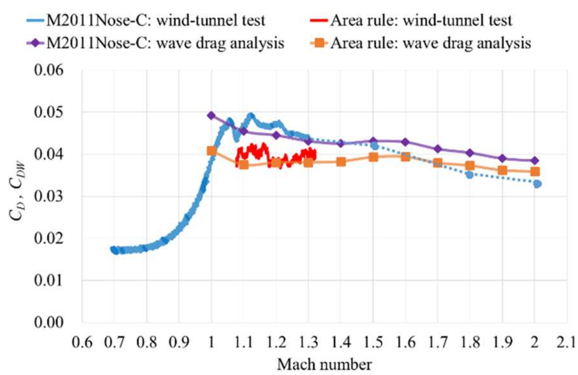


Fig. 12. Results of preliminary wind-tunnel tests and wave drag analysis on the drag reduction by the area rule.

6. Preliminary Flight Tests

6.1 A Prototype Vehicle of the 1st Generation and its Flight Tests

Prior to construction of the supersonic vehicle, a prototype with the configuration M2006prototype was designed and fabricated in order to verify the subsonic flying characteristics of the vehicle configuration through flight tests [1]. Its overall appearance is shown in Fig. 13. Its total takeoff mass is 27.0 kg including fuel of 4.6 kg. Its propulsion system is model-scale twin turbojet engines available on the market. Their rated total thrust is 330N at a sea-level static condition and the maximum airspeed for level flight is predicted to be 104m/sec according to the wind-tunnel test data. Its nickname is OHWASHI (Steller's Sea Eagle) which was selected by an advertised prize contest.

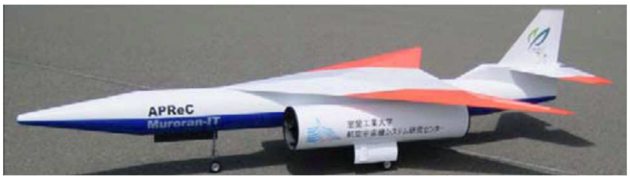


Fig. 13. Overall appearance of the fabricated prototype vehicle.

For onboard data acquisition, a combined GPS/INS navigation recorder, an air data sensor (ADS) including a 5-hole Pitot tube, a control signal detector, a pair of electric control units for the twin turbojet engines, and a small video camera for recording the outside views were installed onboard.

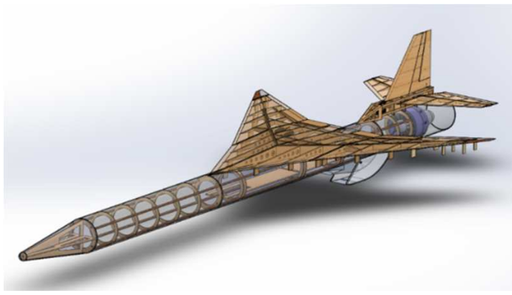
The flight tests of the prototype vehicle were carried out in August 2010 and July 2011 at the Shiraoi Airfield nearest to Muroran Institute of Technology. The vehicle was radio-controlled by a pilot on the ground. The appearance of the prototype vehicle ascending just after takeoff is shown in Fig. 14. The vehicle circled six times above and around the runway for 4 minutes and a half. Its flight stability and controllability were quite adequate. Its aerodynamics in real subsonic flights were analyzed on the basis of the data acquired onboard [1].

Fig. 14. The prototype vehicle ascending just after takeoff.

6.2 Construction of Subscale Vehicles for Smaller-scale Flight Tests

Flight tests with a full-scale vehicle as described above are quite laborious and costly. In order to realize more cost-effective and repeated flight tests, a 1/2-scale vehicle for the 1st generation and a 1/3-scale vehicle for the 2nd generation are designed and are being constructed as shown in Fig. 15. Their main wings, tails, fuselage, and nose are equivalent in shape and dimension, in accordance with the similarity in the configurations M2006prototype and M2011. Subsonic flight tests will be carried out in this and next fiscal year for aerodynamic characterization in realistic flight conditions.

(a) Constructed ½-scale vehicle with the configuration M2006prototype.



(b) Structural design of the 1/3-scale vehicle with the configuration M2011.

Fig. 15. Subscale vehicles for smaller-scale flight tests.

7. Conclusions

With the aims of creating and validating innovative fundamental technologies for high-speed atmospheric flights, a small scale supersonic flight experiment vehicle was designed as a flying test bed. Two generations of aerodynamic configuration with a cranked-arrow main wing were proposed. Concerning their propulsion system, twin counter-rotating axial fan turbojet (CRAFT) engines were proposed for the 1st generation, whereas an air-turbo ramjet gas-generator cycle (ATR-GG) engine was proposed for the 2nd generation. Their aerodynamic stability and controllability were found to be favorable through wind tunnel tests. On the basis of the aerodynamic characterization and propulsion design analysis, flight capability was predicted to be appropriate for realization of supersonic flights up to Mach 2. Prior to the construction of the supersonic vehicles, a full scale prototype vehicle and subscale vehicles are designed and fabricated in order to verify the subsonic flying characteristics through flight tests. In addition, preliminary flight tests of the 1st-generation prototype vehicle were carried out in 2010 and good flight capability was demonstrated.

Thus the proposed supersonic flight experiment vehicle will be realized in near future. This prospective flight experiment vehicle will be applied to flight verification of innovative fundamental technologies for high-speed atmospheric flights such as turbo-ramjet propulsion with endothermic or biomass fuels, MEMS and morphing techniques for aerodynamic control, aero-servo-elastic technologies for efficient aerodynamic control with low-stiffness structure.

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Contact Author Email Address

mailto:mizobata@mmm.muroran-it.ac.jp

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