High Speed and High Angle of Attack
Aerodynamic Characteristics of
Winged Space Vehicle

By

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(September 25, 1987)

Summary: Static aerodynamic characteristics of winged space vehicle is investigated through a series of wind tunnel testing. This report includes a summary of the test results and associated considerations. The tests were conducted and supported by Working Group for Winged Space Vehicle of Institute of Space and Astronautical Science (ISAS). Attention has been concentrated on both longitudinal and lateral/directional, high angle of attack flight capability at high speed flight condition of the vehicle for the accomplishment of the reentry flight, so that three types of tail configuration are investigated, that are single and double-tails and tip-fin configurations. Test results are summarized in terms of aerodynamic coefficients and their derivatives. Discussions based on the test results are made to find out the relations between vehicle configuration and various aerodynamic and flight dynamic characteristics, which refers the high angle of attack flight criteria of current high-performance airplanes.

Key words: Winged Space Vehicle, Aerodynamics, Flight Dynamics, High-Angle-of-Attack Flight.

1. Introduction

Hypervelocity flight in the atmosphere brings about a lot of problems in the extensive fields of technology and it requires many challenging tasks. Several kinds of development plan of winged space vehicle as the US Space Shuttle or much more advanced concepts are proposed in the Unite States, Europe and Japan. They are all going to accomplish a reentry flight from low earth orbit or an intercontinental flight. At present, the US Space Shuttle is an only vehicle which not only realizes such a flight but achieves a partly reusable space transportation system as a launch vehicle. However the vehicles in the next generation are expected to realize a fully reusable or an aircraft-type operation.

In the aerodynamic and flight dynamic design of such vehicles, they must possess a sufficient performance to accomplish reentry flight from low earth orbit and safety landing to a conventional run way. General features of these vehicles are summarized as follows.

1. High angle of attack reentry flight to realize moderate deceleration and to avoid excessive aerodynamic heating at hypersonic flight regime.
2. Unpowered horizontal landing with a lifting surfaces as small as possible.
3. Sufficient stability and controllability throughout entire ranges of Mach number and angle of attack that these vehicles experiences during reentry to final landing.

An emphasis is expressed that these vehicles must meet a requirement on being a rocket vehicle as a fully reusable space transportation system, in which requirement on weight is extremely severer than that for conventional airplane. For instance, the center of gravity is located at 60% of total length of the vehicle or more aft-ward position, because of the weight-saved tank structure for propellants and rocket engines located at the aft end [1]. And it must be remarked that requirements on flight characteristics to these vehicles may be different from those for conventional airplanes [2], so that the flight control strategy must be an unremovable design issue in the design of aerodynamic performances.

To realize the vehicle’s configuration so as to satisfy such requirements on reentry flight, investigations must be performed extensively within the wide ranges of Mach number and of angles of attack. As for the US Space Shuttle, enormous amount of wind tunnel testing have been carried out [3] and those results are partly available [4, 5 etc]. In the preliminary design phase of such vehicles, it is necessary to investigate various possibilities in configuration so as to get a better understanding of the general features of such vehicle’s aerodynamic characteristics or for the aerodynamically optimum design.

In the reentry flight of such a vehicle, it must perform a large drag configuration, so that it is capable of trim at high angle of attack attitude in hypersonic flight regime, and it must have a sufficient controllability to perform a bank maneuver during its hypersonic reentry flight regime. These performances are required in order to trace a low aerodynamic heating trajectory and to gain a cross range during reentry to a landing site [6, 7]. As for the US Space Shuttle, high angle of attack longitudinal trim and the control of vehicle’s drag are performed by use of the integrated deflections of control surfaces such as elevator, body flap and speed brake. In addition, difficulties in achieving the sufficient lateral/directional stability and controllability took place because of the poor directional stability and less effectiveness of rudder for achieving a controlled bank authority in such a hypersonic flight condition. The flight control strategy related to such a bank maneuver of the Space Shuttle orbiter had been directed to utilize a negative LCDP (Lateral Control Departure Parameter), which is an index of proverse/adverse roll motion due to the aileron deflection, at the hypersonic flight condition in the preliminary design phase of the flight control system. As the LCDP changes its sign from negative to positive, with decreasing vehicle’s flight Mach number, conventional control law utilizing rudder coordination would have been activated [8]. However, the definite value and the sign change of the LCDP were not assured by analysis of the uncertainty in the aerodynamic coefficients. Therefore, they were obliged to compensate the side slip angle associated with the bank maneuver or the roll control augmented by the torques of reaction control systems (RCS), and proverse bank control law by use of the aileron with the RCS augmentation is employed in the hypersonic flight regime [9, 10]. This requires the consumption of RCS fuel and results in weight penalty. Thus, the requirements on the
trim capability at high angle of attack attitude and the maneuverability in high speed condition in the reentry flight cause unconventional use of control surfaces and RCS or the combination of both of them, as compared with those of conventional airplanes.

As for the lateral/directional flight characteristics at high angles of attack in low speed flight condition, extensive analyses have been conducted in relation to the spin susceptibility or the "departure" characteristics of the fighter-type aircraft [11–15]. LCDP presented above is one of the parameters to determine the controllability in such a flight condition. Another one which determines the vehicle's stability in these analyses is $C_{n_{B,DYN}}$, that corresponds to the wind-axis directional stability derivative. Such an aircraft encounters an abrupt change in lateral/directional stability and controllability at low speed flight condition because of the unsymmetric wing stall or the interaction between body-wake and tails at a certain attitude, and difficulties in predicting such a departure characteristics arise. On the other hand, the present reentry vehicle does not experience such a discontinuity in both longitudinal and lateral/directional aerodynamic characteristics in high supersonic to hypersonic flight condition even at high angle of attack flight conditions [5, 16, 17]. Therefore, present reentry vehicle is able to employ the criteria for the high angle of attack characteristics of the conventional aircraft described above as that for the nominal flight criteria in a reentry flight condition.

In the preliminary design study of Single-Stage-To-Orbit (SSTO) vehicle [1, 18, 19], the possibilities in configuration are investigated in relation to the flight control requirements, where tip-fin-type tail configuration is proposed. Alternative design studies on the present Space Shuttle orbiter which replaces the vertical tail by tip-fins is also proposed [20, 21]. These are directed to save the vehicle’s weight, which is significantly severe requirement on SSTO, and to improve the lateral/directional flight capability in hypersonic flight regime. In the latter's proposal, Mach number at which purely aerodynamic flight control is activated or at which the rudder is activated without the use of RCS augmentation is improved to be up to 7, whereas the present baseline Shuttle orbiter deactivates RCS at Mach number of 1.0 [17], by a benefit of a better effectiveness of rudders equipped on tip-fin or so called tip-fin-controller at hypersonic flight regime, which is related to the foregoing sign of LCDP. In these configurations, directional stability is inherently negative, so that the active flight control capability is required throughout the entire reentry flight, whereas recent configurations of ESA’s HERMES also employs tip-fins instead of the conventional vertical tails [22]. However, the requirement on the structural weight ratio and the center of gravity location is different from those of the future vehicles which is not only the reentry vehicle but the fully reusable rocket vehicle at the same time. Although the Space Shuttle orbiter is also identical to such vehicles in a way, it has rocket engines as a main propulsion. In this sense, such a recoverable winged payload seems to be designed to have the positive directional stability by tip-fins up to relatively higher Mach numbers. Furthermore, vehicles employing airbreathing propulsion systems, recently proposed in several organizations, requires another feature of aerodynamic characteristics in contrast to such weight properties and the
propulsive performances. Any way, the selection of the vertical tail configuration is a major concern in designing such winged reentry vehicles. A part of the purpose of the present study is to understand how the promising flight control be achieved aerodynamically, and to identify the limitation of the purely aerodynamic flight control in terms of angles of attack and Mach numbers.

Author and others have carried out a series of wind tunnel testing of winged space vehicle whose shape is preliminarily designed for the test vehicle [23] which is directing the future single-staged vehicle. Based on the results of these testing, some degrees of improvement in aerodynamic characteristics of this vehicle has been conducted, and aerodynamic characteristics which attains a sufficient stability and controllability during reentry flight have been taken into account. These improvements are mainly directed to achieve;

1. sufficient longitudinal trim capability by elevator at high angle of attack in hypersonic speed region,
2. higher lift to drag ratio at low speed region,
3. sufficient Lateral/Directional stability and controllability based upon requirements on flight dynamic characteristics, and to gain
4. much informations on lateral/directional stability and controllability with various tail configurations.

In the present series of wind tunnel testing, possibilities in tail configuration, that are single-tailed, double-tailed and tip-fin controller type ones are prepared and tested in order to obtain the knowledges about the characteristics of these configurations in relation to the lateral/directional stability and controllability at high angle of attack in the high speed flight condition.

In the following chapters, description of wind tunnel test model studied, test facilities and test condition of them and aerodynamic coefficient of the vehicle as a test result are presented. Discussions which refer the aerodynamic characteristics mainly related to the longitudinal stability and trim capability and lateral/directional stability and controllability at high angle of attack in the high speed region based upon the results of three types of tail configuration are also presented. It is needed in the aerodynamic design of aircraft that the evaluation of the aerodynamic characteristics is made with simplified correlations by use of the static aerodynamic coefficient before the complete 6-degree-of-freedom flight simulation or the linearized analyses. Here, the characteristic aerodynamic properties of the winged vehicle mentioned above are taken into account, and the aerodynamic coefficients of the present test result are expressed in terms of the criteria based on the foregoing high angle of attack flight characteristics of the advanced aircraft and the Space Shuttle orbiter.

2. Vehicle Configuration and Wind Tunnel Test Model

Vehicle configuration investigated in the present study is an improved one of HIMES (Highly Maneuverable Experimental Space) Vehicle [24], whose concept is
proposed as a technology test bed for the development of the future space transportation system. This vehicle is a fully reusable, rocket powered winged vehicle, and is designed to be given an aerodynamic characteristics which these future vehicles commonly possess as described in the previous chapter. Furthermore, requirements for achieving a reentry flight and horizontal landing are also very close to those of future vehicles.

Fig. 2-1 shows the basic vehicle configuration proposed for HIMES vehicle at a second stage of aerodynamic design that is as a result of improvement of former configuration C-2 [23], and is coded C-4. Major difference between them is a body shape, that has axially symmetric cross section and whose finness ratio is greater than that of C-2. The vehicle’s dimensions are also presented in Table 2-1. Center of gravity of the vehicle is assumed to be located at 64% of total length of the vehicle. In the present study, hence an attention is concentrated on the high angle of attack flight dynamic characteristics of the vehicle, three kinds of tail configuration are prepared for the investigation of lateral/directional stability and controllability. These are double-tailed one as a base line, single-tailed and tip-fin-type configurations. Vehicle’s control surfaces are conventional elevon, and rudder. Elevon is used to act as elevator and aileron. The wing sections of three types of tail are conventional NACA-0012 airfoils for single and double-tailed configurations, whereas that of the tip-fin is composed of an NACA-0012 as a forward part of the fin and a following flat plate. Thus, the trailing edge of the tip-fin is boat-tailed. Hence the tail areas of double-tail and single-tail are the same, that of tip-fin is half of the single and double-tails. The rudder of the double-tail and tip-fin configuration is made up of rear half of the tail planform, whereas that of single-tail is a rear quarter of the tail so as to have the same rudder area as the double-tail configuration. The rudders of tip-fin are split-typed, and the outer sides of the fin deflects as rudders. These variations in the tail and the rudder
Table 2-1. Dimensions of vehicle model

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Length</td>
<td>188.6 mm</td>
</tr>
<tr>
<td>Wing Span</td>
<td>139.7 mm</td>
</tr>
<tr>
<td>Body Max. Width</td>
<td>41.2 mm</td>
</tr>
<tr>
<td>Base Area</td>
<td>1310 mm²</td>
</tr>
<tr>
<td>Wing Area (reference area)</td>
<td>7131 mm²</td>
</tr>
<tr>
<td>(exposed)</td>
<td>3294 mm²</td>
</tr>
<tr>
<td>Sweep Back (leading edge)</td>
<td>40.0 deg.</td>
</tr>
<tr>
<td>Root Chord</td>
<td>54.29 mm</td>
</tr>
<tr>
<td>Tip Chord</td>
<td>13.57 mm</td>
</tr>
<tr>
<td>Aspect Ratio (total)</td>
<td>3.26</td>
</tr>
<tr>
<td>(exposed)</td>
<td>2.86</td>
</tr>
<tr>
<td>Airfoil</td>
<td>NACA-0012</td>
</tr>
<tr>
<td>Mean Aerodynamic Chord</td>
<td>48.09 mm</td>
</tr>
<tr>
<td>Dihedral</td>
<td>5.0 deg.</td>
</tr>
<tr>
<td>Elevon Area (per side)</td>
<td>658 mm²</td>
</tr>
<tr>
<td>Chord</td>
<td>13.57 mm</td>
</tr>
<tr>
<td>Double Tail Area (per side)</td>
<td>663 mm²</td>
</tr>
<tr>
<td>Chord (Root)</td>
<td>28.6 mm</td>
</tr>
<tr>
<td>(Tip)</td>
<td>17.9 mm</td>
</tr>
<tr>
<td>Rudder Area (per side)</td>
<td>332 mm²</td>
</tr>
<tr>
<td>Chord (Root)</td>
<td>14.3 mm</td>
</tr>
<tr>
<td>(Tip)</td>
<td>8.9 mm</td>
</tr>
<tr>
<td>Single Tail Area</td>
<td>1326 mm²</td>
</tr>
<tr>
<td>Chord (Root)</td>
<td>40.4 mm</td>
</tr>
<tr>
<td>(Tip)</td>
<td>22.2 mm</td>
</tr>
<tr>
<td>Rudder Area</td>
<td>255 mm²</td>
</tr>
<tr>
<td>Chord (Root)</td>
<td>14.3 mm</td>
</tr>
<tr>
<td>(Tip)</td>
<td>8.9 mm</td>
</tr>
<tr>
<td>Tip-fin Area (per side)</td>
<td>245 mm²</td>
</tr>
<tr>
<td>Chord (Root)</td>
<td>12.9 mm</td>
</tr>
<tr>
<td>(Tip)</td>
<td>10.0 mm</td>
</tr>
<tr>
<td>Rudder Area (per side)</td>
<td>123 mm²</td>
</tr>
<tr>
<td>Chord (Root)</td>
<td>7.0 mm</td>
</tr>
<tr>
<td>(Tip)</td>
<td>5.0 mm</td>
</tr>
</tbody>
</table>

Center of Gravity                  | 120.68 mm (64% from nose)

configurations are presented in Fig. 2-2.

Wind tunnels used for the study are transonic (M=0.7 to 1.3), supersonic (M=1.6 and 2.5) and hypersonic (M=5) tunnels [25, 26, 27] of National Aerospace Laboratory (NAL) in Tokyo. Test conditions are summarized in Table 2-2 and coverage of the test in terms of Mach number and angle of attack is presented in Fig. 2-3.

In the present study, all of the aerodynamic coefficients and the derivatives of them are expressed as the function of Mach number and angle of attack. Derivatives related to side slip angle are processed by data which is obtained by use of sting support deflected by 5 degree to the β-direction in transonic and supersonic testing and 3 degrees in hypersonic testing, where the linearity in these lateral/directional coefficients are taken into account. All the aerodynamic coefficients and their
derivatives are expressed according to the conventional aircraft definitions as shown in Table 2-3. Deflection angles of control surfaces such as elevon and rudder are defined as shown in Fig. 2-4. Definition of coordinate systems (body fixed axis and wind axis), angle of attack and angle of side slip are also shown in the figure.
Table 2-3. Definition of aerodynamic coefficients and their derivatives

<p>| | | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>$C_s=F_s/QS$</td>
<td>$C_p=F_p/QS$</td>
<td>$C_z=F_z/QS$</td>
</tr>
<tr>
<td>$C_l=M_l/QS_b$</td>
<td>$C_m=M_m/QS_c$</td>
<td>$C_n=M_n/QS_b$</td>
</tr>
<tr>
<td>$C_{L}=\text{LIFT/QS}$</td>
<td>$C_{D}=\text{DRAG/QS}$</td>
<td></td>
</tr>
</tbody>
</table>

\[
\begin{align*}
(\alpha) &= \frac{\partial}{\partial \alpha} \\
(\beta) &= \frac{\partial}{\partial \beta} \\
(\delta_e) &= \frac{\partial}{\partial \delta_e} \\
(\delta_a) &= \frac{\partial}{\partial \delta_a} \\
(\delta_r) &= \frac{\partial}{\partial \delta_r} \\
(\delta_{SB}) &= \frac{\partial}{\partial \delta_{SB}} \\
\end{align*}
\quad (1/\text{deg})
\]

- $Q$: dynamic pressure
- $S$: reference area
- $c$: mean aerodynamic chord
- $b$: wing span
- $\delta_e$: elevator deflection angle
- $\delta_a$: aileron deflection angle
- $\delta_r$: rudder deflection angle

\[\delta_r(L) = \left(\delta_r(L) - \delta_{r}(R)\right)/2\]

- $\delta_{r}(L)$: left side rudder deflection angle
- $\delta_{r}(R)$: right side rudder deflection angle for double tail configuration

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Fig. 2-4. Definition of coordinate system and control surface deflection.
3. Test Results

Test results are presented in terms of longitudinal and lateral/directional aerodynamic coefficients. Longitudinal aerodynamic coefficients $C_L$, $C_D$ and $C_m$ are presented in Fig. 3-1, where results on the elevator deflection are also presented. The derivatives of lift, drag and pitching moment coefficients with respect to elevator deflection are presented in Fig. 3-2. In the longitudinal results of the highest Mach number, data is not obtained partly by annomaries in measurement, and they are supplemented by broken lines, which are estimated by the data of former series of testing [23].

Lateral/directional aerodynamic coefficients such as $C_Y$, $C_l$ and $C_n$ are presented in terms of derivatives with respect to side slip angle (Fig. 3-3) and those of aileron and rudder deflection angle (Fig. 3-4 and Fig. 3-5). In the figures of derivatives with respect to the side slip angle and rudder deflection, results of tail-on and off configuration and those of single-tail, double-tail and tip-fin configuration are also presented for comparison throughout the entire Mach number region studied.

Data accuracy of measurement based on the repeatability and the result of compensation of forces and moments, resulting from various reasons such as setting error of the model, gauge balance and sting support in each testing is estimated as about

- 0.005 for $C_L$, $C_D$ and $C_Y$
- 0.002 for $C_m$
- and 0.001 for $C_l$ and $C_n$

in terms of the magnitude of measured aerodynamic coefficients (not of the processed aerodynamic derivatives). These values are of the worst condition which are at the lowest speed condition of transonic testing and at hypersonic testing. Derivatives of elevator deflection and lateral/directional aerodynamic coefficients presented in the following results are obtained by data that are 3 and 5 degrees of side slip angle, 10 or 20 degrees of elevator deflection angle, 5 degrees of aileron deflection and 30 or 60 degrees of rudder deflection respectively, which are presented in each data.

4. Discussion

4-1. Longitudinal Aerodynamic Characteristics

General Remarks

As shown in Fig. 3-1, lift and drag characteristics are fairly similar to those of conventional aircraft from low to high Mach number region. Even at high angle of attack attitude condition, significant non-linearity or discontinuity in these coefficients are not observed, and no abrupt change in the longitudinal characteristics which appears in the low speed characteristics of the conventional airplanes is not observed in this range any way.
Fig. 3-1-a. Longitudinal aerodynamic coefficient with elevator deflection (M=0.7).

Fig. 3-1-b. Longitudinal aerodynamic coefficient with elevator deflection (M=0.8).
Fig. 3-1-c. Longitudinal aerodynamic coefficient with elevator deflection (M=0.9).

Fig. 3-1-d. Longitudinal aerodynamic coefficient with elevator deflection (M=1.0).
Fig. 3-1-e. Longitudinal aerodynamic coefficient with elevator deflection (M=1.1).

Fig. 3-1-f. Longitudinal aerodynamic coefficient with elevator deflection (M=1.2).
Fig. 3-1-g. Longitudinal aerodynamic coefficient with elevator deflection (M=1.3).

Fig. 3-1-h. Longitudinal aerodynamic coefficient with elevator deflection (M=1.6).
Fig. 3-1-i. Longitudinal aerodynamic coefficient with elevator deflection (M=2.5).

Fig. 3-1-j. Longitudinal aerodynamic coefficient with elevator deflection (M=5.0).
Fig. 3-2-a. Longitudinal aerodynamic derivatives of elevator $M=0.7–1.4$ (based on $\delta_e=-10$ deg data).

Fig. 3-2-b. Longitudinal aerodynamic derivatives of elevator $M=1.0–1.3$ (based on $\delta_e=-10$ deg data).
Fig. 3-2-c. Longitudinal aerodynamic derivatives of elevator $M=1.6$ (based on $\delta e=10, -10$ and $-20$ deg data).

Fig. 3-2-d. Longitudinal aerodynamic derivatives of elevator $M=2.5$ (based on $\delta e=10, -10$ and $-20$ deg data).
Fig. 3-2-e. Longitudinal aerodynamic derivatives of elevator $M=5.0$($\delta_e = -10$).

Fig. 3-3-a. Lateral directional aerodynamic derivatives of side slip angle ($M=0.7$).
Fig. 3-3-b. Lateral directional aerodynamic derivatives of side slip angle (M=0.8).

Fig. 3-3-c. Lateral directional aerodynamic derivatives of side slip angle (M=0.9).
Fig. 3-3-d. Lateral directional aerodynamic derivatives of side slip angle (M=1.0).

Fig. 3-3-e. Lateral directional aerodynamic derivatives of side slip angle (M=1.1).
Fig. 3-3-f. Lateral directional aerodynamic derivatives of side slip angle (M=1.2).

Fig. 3-3-g. Lateral directional aerodynamic derivatives of side slip angle (M=1.3).
Fig. 3-3-h. Lateral directional aerodynamic derivatives of side slip angle (M=1.6).

Fig. 3-3-i. Lateral directional aerodynamic derivatives of side slip angle (M=2.5).
Fig. 3-3-j. Lateral directional aerodynamic derivatives of side slip angle (M=5.0).

Fig. 3-4-a. Lateral directional aerodynamic derivatives of aileron deflection (M=0.7–1.0, based on $\delta_a=5$ deg, $\delta_e=0$ deg data).
Fig. 3-4-b. Lateral directional aerodynamic derivatives of aileron deflection (M=1.0–1.3, based on δa=5 deg, δe=0 deg data).

Fig. 3-4-c. Lateral directional aerodynamic derivatives of aileron deflection (M=1.6, based on δa=5 deg, δe=0 and −5 deg data).
Fig. 3-4-d. Lateral directional aerodynamic derivatives of aileron deflection (M=2.5, based on \( \delta a=5 \text{ deg}, \delta e=0 \text{ and } -5 \text{ deg data} \)).

Fig. 3-4-e. Lateral directional aerodynamic derivatives of aileron deflection (M=5.0, based on \( \delta a=5 \text{ deg}, \delta e=0 \text{ deg data} \)).
Fig. 3-5-a. Lateral directional aerodynamic derivatives of rudder deflection (M=0.7 based on δr=30 deg data).

Fig. 3-5-b. Lateral directional aerodynamic derivatives of rudder deflection (M=0.8 based on δr=30 deg data).
Fig. 3-5-c. Lateral directional aerodynamic derivatives of rudder deflection ($M=0.9$ based on $\delta r=30$ deg data).

Fig. 3-5-d. Lateral directional aerodynamic derivatives of rudder deflection ($M=1.0$ based on $\delta r=30$ deg data).
Fig. 3-5-e. Lateral directional aerodynamic derivatives of rudder deflection ($M=1.1$ based on $\delta r=30$ deg data).

Fig. 3-5-f. Lateral directional aerodynamic derivatives of rudder deflection ($M=1.2$ based on $\delta r=30$ deg data).
Fig. 3-5-g. Lateral directional aerodynamic derivatives of rudder deflection ($M=1.3$ based on $\delta r=30$ deg data).

Fig. 3-5-h. Lateral directional aerodynamic derivatives of rudder deflection ($M=1.6$ based on $\delta r=30$ deg data).
Fig. 3-5-i. Lateral directional aerodynamic derivatives of rudder deflection ($M=2.5$ based on $\delta r=30$ deg data).

Fig. 3-5-j. Lateral directional aerodynamic derivatives of rudder deflection ($M=5.0$ based on $\delta r=30$ deg data).
Longitudinal Stability

Pitching moment coefficient slope which determines longitudinal static stability characteristics is negative and aerodynamically stable at subsonic to low supersonic range except for angle of attack greater than 10 degrees at subsonic speed range and for small angle of attack in hypersonic speed range. In the subsonic speed range, although the number of data points is relatively smaller than those of the other speed ranges, considerable non-linearity is observed in pitching moment curve. It is not favorable in terms of flight dynamic characteristics and it will be improved by the installation of forward part of delta wing [23, 28]. Non-linearity in elevator effectiveness is also observed in Mach number 0.8 and 0.9, which seems to be caused by the position of shock wave on main wing and interaction between this and elevator deflection.

As the Mach number increases, pitching moment coefficient changes its characteristics gradually, where significant difference is observed among the result of Mach number of 1.6, 2.5 and 5. In the highest Mach number, it is longitudinally unstable around small angles of attack, whereas it becomes stable at angle of attack greater than 15 degrees.

Longitudinal Trim

Maximum value of untrimmed lift to drag ratio (L/D) is presented in Fig. 4-1 where angle of attack at which this maximum L/D is realized is also presented. In subsonic region, longitudinal trim is desirable to be achieved at about 10 degrees of angle of attack. Maximum L/D at low speed region which determines landing capability is as much as 5, and it seems to be sufficient as compared to the Space Shuttle orbiter.

Effect of elevator deflection to the pitching moment coefficient \( C_m_{e} \) is as much as 0.01 per degree in subsonic region. It is smaller as Mach number increases. In the

![Graph](image-url)  
*Fig. 4-1. Untrimmed maximum lift to drag ratio.*
higher Mach number region, $Cm_{\delta_e}$ is about half to one third of that of subsonic range. Test result shows that it is greater at high angle of attack and at large deflection of elevator. This implies that the Newtonian flow approximation may be possible in predicting elevon deflection coefficient in these and much higher Mach number region.

As is seen in Fig. 3-1-j, high angle of attack longitudinal trim and longitudinally stable flight characteristics are accomplished by the present configuration. Although the longitudinal trim and stability at low angle of attack in the highest Mach number range are not attained, it may be sufficient for the reentry vehicle because of its limited flight history at reentry flight. Result of pitching moment coefficient at Mach number 5 shows a typical characteristics in hypersonic flight condition, and no substantial difference in pitching moment curve may exist at much higher Mach number region [23]. Fig. 4-2 shows a summarized longitudinal trim capability of the vehicle based on the present test results of $C_m$ and $C_m_{\delta_e}$. It is observed that high angle of attack trim is achieved in high supersonic to hypersonic speed region and that angle of attack which realizes high L/D at low speed region is attained within an appropriate elevator deflection. As a result, longitudinally trimmable band and aerodynamically stable region in terms of Mach number and angle of attack is overlapping by the present configuration, and the requirement on longitudinal flight dynamics at the reentry flight from high to low Mach number region is satisfied.

4-2. Lateral/Directional Aerodynamic Characteristics

General Remarks

Aerodynamic coefficients related to lateral/directional stability and controllability are influenced very much by both angle of attack and Mach number as shown in the results presented in the previous sections. As for the baseline double-tail configura-
tion, negative and stable dihedral effect in rolling moment coefficient slope is attained within entire Mach number region. As shown in the test results, it is observed that rolling moment which is generated by tail has a great effect. On the other hand, yawing moment coefficient which determines the directional stability is difficult to attain the performance which conventional aircraft possesses. Although it is positive in subsonic to low supersonic region for single and double-tail configurations, it is negative at high angle of attack in higher Mach number region in spite of existence of these tails. Furthermore, it becomes more unstable as angle of attack increases. As the effect of tail to the directional stability becomes smaller as Mach number increases and side force produced by body is not so influenced by Mach number, this directional instability seems to be unavoidable in much higher speed region. Of course, extremely large tail may solve the problem but it may not be of a practical solution.

In the low subsonic speed region, conventional aircraft experiences an abrupt change in lateral directional stability characteristics at high angle of attack attitude condition, which is related to the stall due to flow separation on wing. However, in the characteristics of present winged vehicle, it is observed that no abrupt change as described above takes places in both rolling and yawing moment coefficients at high angle of attack in such a high speed region.

Comparison of side slip angle derivatives at supersonic speed between double-tail and single-tail configuration reveals that single-tail is advantageous in low supersonic region and that double-tail has an advantage at high angle of attack attitude condition in terms of directional stability derivatives. Associated differences in dihedral effect of these tail modification is greatly affected as shown in the figures. It is pointed out that dihedral effect of single-tail configuration in Mach number of 1.6 at angle of attack greater than 20 degrees shows reversal effectiveness, and the same tendency is observed in Mach number of 2.5. On the other hand, tip-fin configuration has a relatively small effect that increases directional stability because of its small size as compared with the other configurations, and associated rolling moment is also substantially negligible as compared to those in the other tail configurations. From view point of flight dynamic characteristics, balance between dihedral effect and directional stability is so important a design issue that tail configuration must be determined with a sufficient analysis of stability and controllability. Further investigations based on these data are presented in the following sections.

Aileron effectiveness is sufficient to compensate the rolling moment caused by side slip. It is also observed that the greater the angle of attack and the deflection angle are, the greater the effectiveness is, as seen in the derivatives of elevator effectiveness. On the contrary, induced yawing moment associated with aileron deflection $C_{n_{ba}}$ shows a rather complicated behavior, where it has a proverse yaw characteristics in subsonic region and has an adverse yaw characteristics in supersonic region. In addition, it is affected greatly by both angle of attack and elevator position. This is an important aerodynamic derivatives to determine the controllability in flight dynamic characteristics especially at high angle of attack attitude condition where the vehicle’s directional stability is of poor characteristics.

Yawing moment produced by rudder deflection $C_{n_{3r}}$ of the single and double-tails
seems to have a sufficient control moment as compared with the directional stability coefficient in transonic region. However, it has less effect at high angle of attack in higher Mach number region. The higher the angle of attack and Mach number are, the worse the effectiveness is. This decrease is caused by the body wake which reduces the dynamic pressure acting on tail and control surface on it for single and double-tail configurations. The way of decrease in rudder effectiveness of tip-fin seems to be different from the other configurations, because the outer side of tip-fin faces the free streams more than the other tails. Any way, this derivative is also one of the most important ones in flight control characteristics, as discussed in the following sections.

**Wind Axis Directional Stability**

As for the analyses of high angle of attack flight characteristics of fighter-type-aircraft at low subsonic speed region, criteria for the directional instability is a significant design factor in terms of spin susceptibility, and extensive simulator analyses and flight analyses have been carried out [11-13]. These analyses concluded that the effective directional stability is characterized by

\[ C_{n_{\beta,DYN}} = C_{n_{\beta}} \cos \alpha \frac{I_z}{I_x} C_{l_{\beta}} \sin \alpha \]  \hspace{1cm} (4-1)

instead of \(C_{n_{\beta}}\) at high angle of attack flight conditions, which represents a directional stability about a stability axis. In this sense, vehicle is more stable as angle of attack increases in case that the vehicle has a stable dihedral effect (\(C_{l_{\beta}}<0\)). Since the ratio of moment of inertia \(I_z/I_x\) ranges from 6 to 10 in case of present winged vehicle, this effect is amplified, and it may be possible that this criteria is satisfied in spite of negative directional stability about body fixed axis.

![Graph](image-url)  
*Fig. 4.3-a.  \(C_{n_{\beta,DYN}}\) of various tails (\(M=1.6\)).*
Fig. 4-3-b. $Cn_{p, DYN}$ of various tails (M=2.5).

Fig. 4-3-c. $Cn_{p, DYN}$ of various tails (M=5.0).

Fig. 4-3-a, b and c show the results of $Cn_{p, DYN}$ of present configurations in supersonic (M=1.6 and 2.5) and hypersonic (M=5) speed region, where single-tail, double-tail, tip-fin and tail-off configurations are compared. As shown in the figures, both single and double-tail configurations can make this coefficient positive at angle of attack greater than 15 degrees even in the highest Mach number. It must be remarked that $Cn_{p, DYN}$ is positive, even if it is of the tailless configuration, at angle of attack greater than 25 degrees. Hence, the single-tail configuration is advantageous in terms of this coefficient because of larger value of $C_{l_{\beta}}$ than that of double-tail configuration in the low angle of attack range, it shows the decay in $Cn_{p, DYN}$ at angle of attack
greater than 15 degrees as shown in Fig. 4-3-a and b. This is due to the corresponding decay in the dihedral effect presented in Fig. 3-3-h and i which seems to be caused by the interaction between body-wake and tail. The contribution of tip-fin to $Cn_{\beta,DYN}$ is smaller as compared with the other tails as shown in the figures. This is also due to the lack of $Cl_\beta$ as that of single-tail configuration. As is seen in these figures, effectiveness of tails or tip-fin is decreasing as Mach number increases, and way of decreasing is different among these three types of tail configuration. In such a sense, the tip-fin configuration is favorable for its less sensitivity in Mach number, and the single-tail is the worst among them in hypersonic flight condition. As a result, it is apparently noted that the high angle of attack flight condition is rather favorable requirement in terms of this wind-axis directional stability. It must be noted that the accuracy of $Cn_{\beta,DYN}$ in hypersonic testing is evaluated as much as 0.001, which is of poorer quality than that of the other supersonic ones.

Control Surface Effectiveness

The aerodynamic derivatives related to the lateral/directional stability and controllability such as $Cl_\beta$, $Cn_{\beta}$, $Cl_{\delta_u}$, $Cn_{\delta_u}$, $Cl_{\delta_r}$, and $Cn_{\delta_r}$ are represented in terms of lateral/directional control vectors where effectiveness of aileron and rudder as rolling and yawing moment producers are presented in contrast to the derivatives of side slip angle, all of whose magnitudes are of 1 degree of deflection or side slip angle, respectively. Fig. 4-4-a, b and c are those of double-tail, single-tail and tip-fin configurations for subsonic to hypersonic speed region, and the angle of attack corresponding to each Mach number are assumed to be 10.0, 20.0 and 30.0 degrees where the history of angle of attack during reentry flight has been taken into account. In these figures, aileron effectiveness of single-tail and tip-fin configuration are identical to that of double-tail configuration, whereas interaction between single-tail or tip-fin and aileron deflection is neglected here. From viewpoint of flight control,
control moment of aileron and rudder must have a sufficient magnitude to manage the moment caused by side slip angle that is a result of transient body motion associated with maneuvers of the vehicle or external disturbances.

As is seen in the moment vectors of side slip angle for three types of tail configuration, they varies greatly as Mach number changes. Negative to positive in directional stability is indicated for single and double-tail configurations as Mach number decreases, whereas that of tip-fin is quite different, and it is negative always and unstable dihedral effect in low supersonic to subsonic speed region for tip-fin configuration, because of the poorer directional stability and dihedral effect than those of other configurations.

Although the aileron effectiveness is decreasing as Mach number increases, it is enough to cancel the rolling moment caused by side slip angle within an appropriate deflection angle of aileron for all configurations throughout the entire Mach number range studied. Way of changing from proverse yaw to adverse yaw characteristics is also displayed.

The effectiveness of rudder greatly varies from tail to tail. Although it has a sufficient control moment in subsonic region, it does not have a moment enough to cancel yawing moment caused by side slip angle even for the single and double-tail configuration at Mach number greater than 1.6. It is also indicated that the effectiveness is rather comparable to or less than the yawing moment associated with aileron deflection in these Mach number ranges. It is easily imagined that difficulty in compensating the yawing motion associated with the roll control by aileron with these rudders takes place. Fig. 4-4-d represents the results of enlargement of Fig. 4-4-a, b and c, where decay of the rudder effectiveness itself is compared as Mach number increases. As is seen clearly in the figures, although the rudder effectiveness on the yawing moment of the single-tail configuration is better than that of double-tail at low
supersonic speed range, it decays rapidly as Mach number increases. In case of tip-fin configuration, the rudder effectiveness is smaller because of its small size, whereas the decay of the effectiveness with increasing Mach number and angle of attack is not so influenced as that of double and single-tail configurations. In Fig. 4-4-d, the rudder effectiveness corrected for the same area of the rudder ($Cn_{R\beta} = Cn_{R\beta}S_R(st)/S_R(tf)$ for instance) is also presented, where it is observed that the tip-fin configuration is advantageous in terms of the effectiveness per rudder area at higher Mach number range and higher angle of attack attitude condition. It must be noted that the cross section of the tip-fin is different from other tails in these comparisons, and that the rudder effectiveness will be influenced by the airfoil section as much as the tail and rudder planforms themselves.
Weissman's Criteria

Weissman et al. proposed a criteria in which the relations between control moment and moment caused by side slip angle, presented as the lateral/directional control vectors, are determined in terms of roll control or associated spin susceptibility of aircraft at high angle of attack flight condition [14, 15]. In this criteria, controllability of the vehicle is determined in terms of $Cn_{\beta, DYN}$ described previously and Lateral Control Departure Parameter (LCDP) or Aileron Alone Departure Parameter (AADP). These parameters are defined as

$$
\text{AADP} = \frac{Cn_{ba} - Cn_{\beta}}{C_l_{ba}}
$$

(4-2)

$$
\text{LCDP} = \text{AADP} + K \frac{Cn_{ba} - Cn_{\beta}}{C_l_{ba}}
$$

(4-3)

where $K$ is a rudder coordination factor ($K = -\delta r/\beta$). AADP is a parameter which represents reversal bank motion with aileron alone bank maneuver, and LCDP is that with rudder coordination with respect to the side slip angle. From view point of the flight dynamic characteristics, if both $Cn_{\beta, DYN}$ is positive and LCDP is positive or greater than $-0.0017$ (deg$^{-1}$), ordinary control laws of aircraft or the conventional pilot gain for the man-in-loop control systems can be adopted for the lateral/ directional flight control, and recent fighter-type aircraft are designed so as to have the characteristics in which these parameters be in the region above.

Fig. 4-5-a, b and c show the results of present three types of tail configurations in relation to the $Cn_{\beta, DYN}$ and LCDP with various values of the rudder coordination factor K, where angle of attack is assumed as in the former section. As is seen in the

![Fig. 4-5-a. LCDP and $Cn_{\beta, DYN}$ of double tail configuration.](image)
figures, tendency of single and double-tail configurations is similar each other, whereas that of tip-fin is quite different from others. In the former two configurations, conventional aircraft-type characteristics is attained at Mach number less than 2, whereas in the higher Mach number range, LCDPs tend to be negative due to the decay of rudder effectiveness as shown in Fig. 4-5-a and b. Data for Mach number of 5 shows that considerably large value of rudder coordination factor K is required to attain LCDP $>$ $-0.0017$ (deg$^{-1}$). In this sense, double-tail configuration is more advantageous than the single-tail configuration in Mach number of 5, because of less
rudder effectiveness of single-tail in this speed range. In case of tip-fin configuration, hence both LCDP and $C_{n_{\beta,DYN}}$ are negative even in subsonic to low supersonic region, whereas no substantial differences are observed in Mach number of 5 as compared to the other two tails. This is due to the decay of the tail effectiveness on the lateral/directional stability in hypersonic speed range for both single and double-tail configurations.

The rudder coordination factor K is identical to the autopilot gain from the side slip angle to the rudder deflection angle in the sense of the flight control. It is concluded that extremely large coordination is required for the flight in higher Mach number range by the present configuration of tails and rudders. The limitation of purely aerodynamic flight control is determined in relation to the coordination factor and rudder effectiveness itself. Furthermore, tip-fin configuration requires unconventional flight control laws even in the low supersonic to subsonic flight condition. In much higher Mach number region, where the present wind tunnel testing does not cover, LCDPs seem to tend much more negative and great deal of rudder coordination will be required for the accomplishment of proverse roll control, and this requires the extremely large deflection of rudder, where the limitation due to actuation and aerodynamic heating must be taken into account. Thus, the possibility in which the flight control actively utilizes the adverse roll characteristics (negative LCDP) may arise, or the alternative yaw control devices such as reaction control or additional control surfaces are required for achieving the accomplishment of the lateral/directional control if the proverse roll control strategy (positive LCDP) is employed at the hypersonic reentry flight regime.

5. CONCLUDING REMARKS

Static aerodynamic characteristics of winged space vehicle recently studied in ISAS are obtained as the longitudinal and lateral/directional aerodynamic coefficients and their derivatives through a series of wind tunnel testing. All the coefficients and derivatives are obtained as the function of angle of attack and Mach number. High angle of attack longitudinal trim and stability are investigated. Also made are the comparisons among three types of tail configuration in terms of lateral/directional stability and controllability based on the $C_{n_{\beta,DYN}}$, control vectors and LCDP.

Results of the present study are summarized as follows.

1. Maximum Lift to drag ratio at low speed region is as much as 5 and seems to be sufficient to realize a safety landing to run way.
2. Sufficient longitudinal trim only with elevator and positive longitudinal stability are attained within the required reentry flight history.
3. Directional stability of nominal double-tail configuration ranges slightly positive to negative as Mach number increases, whereas $C_{n_{\beta,DYN}}$ is positive at high angle of attack in supersonic to hypersonic speed range.
4. The single-tail configuration is favorable in low supersonic region, whereas the double-tail comes advantageous at high angle of attack and higher speed region in
Fig. 5-1. Longitudinal trim and stability and controllability boundary of base-line double tail configuration.

terms of directional stability. Its rudder effectiveness almost fades out in hypersonic speed region.

5. Although tip-fin configuration requires unconventional flight control laws because of its small size of fin surfaces, decay of rudder effectiveness is smaller than that of other tails.

Fig. 5-1 presents a summary of the present study for the base-line double-tail configuration, in terms of the longitudinal trim boundary and longitudinal and lateral/ directional stability and controllability boundary such as $C_{m_{\alpha}}$, $C_{n_{\beta,DYN}}$ and $LCDP$. As shown in the figure, the present configuration is capable of performing reentry flight with longitudinally stable and trimmable characteristics, and lateral/ directional stability seems to be attained through out the reentry flight. However, in terms of lateral/directional controllability, the boundary of $LCDP$ cuts across the flight corridor, and significant flight control difficulties may arise in lateral/directional flight dynamic characteristics, and flight control concept must be constructed with this characteristics taken into account. This is caused by the lack of rudder effectiveness and will be worse in much higher speed of flight condition where present study does not cover. It seems to be an inherently given and unavoidable in designing such a winged reentry vehicle. These must be concluded after the sufficient investigations of flight dynamics and flight controls of the vehicle along the trajectory or along the history of Mach number and angle of attack of reentry flight. As for the case of tip-fin configuration, these difficulties are amplified, and analysis associated with the flight control strategy and with the heating of control surfaces is of a great interest.

It must be stated at the end of the discussions that these characteristics are general in designing the vehicles such as present fully reusable rocket vehicle. However, as for
the winged reentry vehicle which does not have a main propulsion system in itself, such as ESA's HERMES, and as for the space vehicles which utilize air-breathing propulsion systems, differences in the center of gravity position and requirement on vehicles structural weight ratio are the decisive factors, so that their characteristics may differ partly from that presented herein.

ACKNOWLEDGEMENT

The author sincerely wishes to acknowledge personnel in transonic, supersonic and hypersonic wind tunnels of National Aerospace Laboratory for their cooperation in executing the present series of wind tunnel testing and measurement. He expresses his great gratitude to Prof. H. Oguchi who is the director of the Working Group for Winged Space Vehicle in ISAS, and Special thanks are due to the late Dr. I. Wada who has been the director of the 1st research division of aerodynamics in NAL. Both of them were contributed to give opportunities to make the present series of wind tunnel testing at NAL. He also expresses his special thanks to Mr. K. Yonemoto, who is currently a temporary research fellow in ISAS from Kawasaki Heavy Industries, for their essential discussions on the flight control and the high-angle-of-attack flight dynamic characteristics of the winged vehicle.

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