JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 42, No. 6, November–December 2005

Aerodynamic Yaw Controller for the Space Shuttle Orbiter

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A wind-tunnel investigation of the effectiveness of an aerodynamic yaw controller mounted on the lower surface of a Space Shuttle Orbiter model body flap was conducted in the Langley 31-Inch Mach 10 tunnel. The controller, consisting of a 60-deg delta fin mounted perpendicular to the body-flap lower surface and yawed 30 deg to the freestream direction, was tested at orbiter angles of attack from 20 to 40 deg at zero sideslip for a Reynolds number based on the wing mean aerodynamic chord of 0.66 × 10⁶. The aerodynamic control characteristics are presented with an analysis of the effectiveness of the controller in making a bank maneuver for Mach 18 flight conditions. The analysis shows that the controller is as effective as the reaction control system in initiating the bank maneuver. These results warrant further studies to determine the aerodynamic heating on the control surfaces and the effects of controller hinge-line cant angle and body-flap deflection on the controller effectiveness.

Nomenclature

b	=	wing span, ft
C_l	=	rolling-moment coefficient, rolling moment/$q_\infty S_{\text{ref}} b$
$C_{l\beta}$	=	variation of rolling-moment coefficient with sideslip angle, per degree
$C_{l\delta a}$	=	variation of rolling-moment coefficient with aileron deflection, per degree
C_m	=	pitching-moment coefficient, pitching moment/$q_\infty S_{\text{ref}}$(cbar)
C_n	=	yawing-moment coefficient, yawing moment/$q_\infty S_{\text{ref}} b$
$C_{n\beta}$	=	variation of yawing-moment coefficient with sideslip angle, per degree
$C_{n\delta a}$	=	variation of yawing-moment coefficient with aileron deflection, per degree
C_p	=	pressure coefficient, $(p_{\text{local}} - p_\infty)/q_\infty$
C_Y	=	side-force coefficient, side force/$q_\infty S_{\text{ref}}$
$C_{Y\beta}$	=	variation of side-force coefficient with sideslip angle, per degree
$C_{Y\delta a}$	=	variation of side-force coefficient with aileron deflection, per degree
cbar	=	mean aerodynamic chord, ft
H	=	altitude, ft
I_{XX}	=	moment of inertia about the body longitudinal axis, slug · ft^2
I_{ZZ}	=	moment of inertia about the body vertical axis, slug · ft^2
N_J	=	number of reaction control system jets firing
P_{local}	=	local surface pressure, psf
p	=	rolling angular velocity, rad/s
p_∞	=	freestream pressure, psf
Re_{cbar}	=	Reynolds number based on wing mean aerodynamic chord
r	=	yawing angular velocity, rad/s
S_{ref}	=	reference wing planform area, ft^2
V_∞	=	freestream velocity, ft/s
X	=	longitudinal body axis
Y	=	lateral body axis
Z	=	vertical body axis
α	=	angle of attack, deg
β	=	angle of sideslip, deg
δ_a	=	aileron deflection angle, $(\delta_{eL} - \delta_{eR})/2$, deg
δ_{BF}	=	body-flap deflection angle, positive, trailing edge down
δ_e	=	elevon deflection angle, positive, trailing edge down
δ_Y	=	yaw controller deflection angle, positive, trailing edge down
φ	=	roll angle about the body longitudinal axis, deg

Subscripts

L	=	left
R	=	right

Introduction

THE control of spacecraft (lifting bodies or winged vehicles) during entry into the sensible atmosphere, if accomplished with movable aerodynamic surfaces, would eliminate the need for the reaction control system (RCS) for this phase of flight. The reaction controls could then be used exclusively for on-orbit attitude control and docking maneuvers. At the high angles of attack required to mitigate the aeroheating during the hypersonic portion of the entry trajectory, conventional vertical tails are ineffective. Pitch and roll control can be maintained with wing trailing-edge controls. Aerodynamic yaw control can be accomplished with wing-tip fins,[1] but the associated structural and thermal protection weights may be unacceptable. To date, the practical solution to the problem is a combination of movable aerodynamic surfaces and reaction controls. The Space Shuttle Orbiter is a lifting configuration with large movable aerodynamic surfaces for pitch and roll control and, before 1998, it used the aft-located side-firing RCS thrusters for yaw control during atmospheric entry. The HL-20 Personnel Launch System[2] was also designed to use a combination of aerodynamic control surfaces and RCS for entry control. In the case of the Space Shuttle Orbiter, additional contingencies during entry have required increased allocations of RCS propellant, thus reducing that available for on-orbit maneuvers. These increased allocations have a negative impact on the mission capability, and for this reason the aerodynamic yaw controller concept becomes more attractive.

The difficulty with aerodynamic yaw control during entry is that the surface must be located in a region of high-energy flow to be effective. The most effective location, from the standpoint of aerodynamic control on a vehicle at high angle of attack, is on the exposed lower surface; however, such a location is subject to severe aerodynamic heating. The control would continually be exposed to this environment, making it difficult to provide sufficient thermal protection. One way to mitigate the effects of this harsh environment is to design the control such that the critical leading edge is exposed only when the controller is deflected. Ladson[3] explored this idea with a deployable ventral stabilizer on the HL-10 at Mach 6.8. The concept envisioned herein embodies a principle in which

Received 5 August 2004; revision received 8 December 2004; accepted for publication 23 December 2004.

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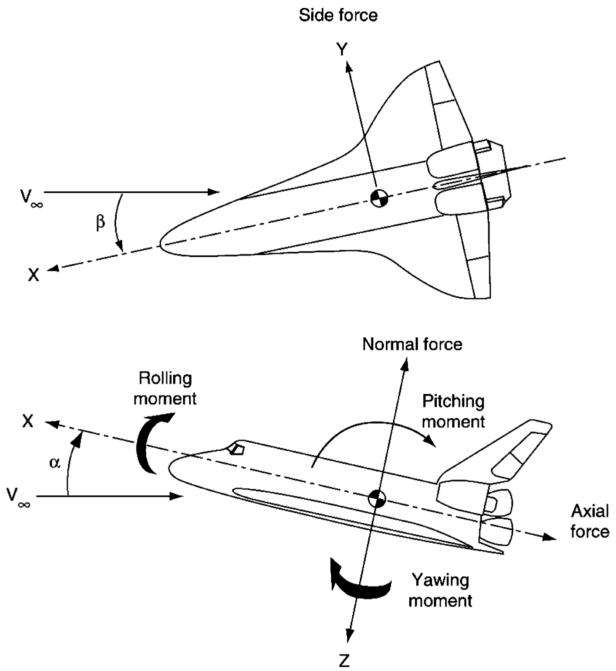


Fig. 1 System of axes, showing positive direction of forces, moments, and angles.

the controller is located on the lower surface of a vehicle such as the HL-20, or as an integral part of a body flap on the Space Shuttle Orbiter. In either case, the controller would lie flush with the adjacent surface until it pivots about a hinge into the stream for control, therefore limiting the time of exposure to the severe heating environment.

This report presents the results of a study of the effectiveness of the controller concept located on the body flap of a 0.0075-scale Orbiter model. The tests were conducted in the Langley 31-Inch Mach 10 tunnel for a model angle-of-attack range of 20 to 40 deg at zero sideslip angle with the body flap alone, and with the controller attached to represent 90-deg deflection; the freestream Reynolds number was 0.66×10^6, based on the model wing mean aerodynamic chord. The increments in the controller aerodynamic parameters obtained from these tests were used in a preliminary analysis of the effectiveness of the controller in performing the entry into an Orbiter bank maneuver at Mach 18 flight conditions taken from the first shuttle entry.

The aerodynamic data are referred to the body-axis system (Fig. 1). All coefficients are based on the wing reference planform area, the wing mean aerodynamic chord, and the wingspan. The moment reference center was located at the nominal vehicle center of gravity, which was 65% of the body length from the nose inner mold line.

Control Concept

The concept of the yaw controller as applied to the orbiter is shown in Fig. 2. The body-flap planform would be modified by making the sides of the body flap parallel to the vehicle X axis (trailing-edge span equal to span at the hinge line) to provide more area for the controllers. As shown in the figure, the tips of the body flap would deflect individually about canted hinges (arbitrarily canted 30 deg in the present study) to provide a right or left yaw moment. Because of the nature of the bank maneuvers used by the Orbiter during entry, these controllers would be used intermittently in the same manner as the yaw RCS to initiate and terminate the maneuvers. Although the controller could be deflected to intermediate angles, it is intended to be deflected fully (90 deg) for the bank maneuvers. As can be seen in the three-view sketch in Fig. 2, the outboard edge of the body flap becomes the leading edge of the controller with a sweep of 60 deg when fully deflected to 90 deg.

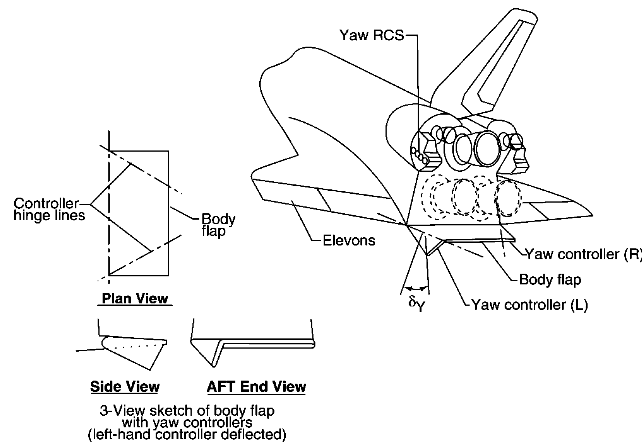


Fig. 2 Sketch showing the yaw controller as applied to the Space Shuttle Orbiter.

Apparatus and Tests

Facility

The Langley 31-Inch Mach 10 tunnel expands heated dry air through a three-dimensional, contoured, water-cooled nozzle into a 31-in.^{2} test section. The nominal test Mach number is 10. The tunnel operates in blowdown mode with run times ranging from 60 to 120 s. The air is heated to approximately 1850°R by an electrical resistance heater with reservoir pressures up to approximately 1500 psia. Models are supported on a hydraulically operated, sidewall-mounted injection system. This tunnel and its capabilities are described in more detail by Miller.[4]

Model

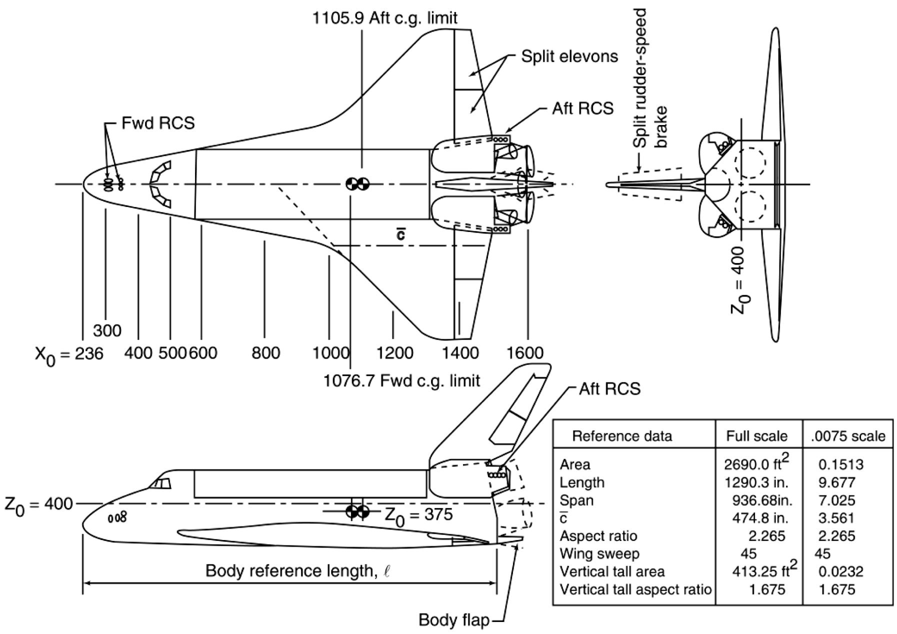
A 0.0075-scale, stainless-steel model with the outer mold lines corresponding to those of the current flight Orbiters was used in the present tests. A three-view sketch of the configuration is shown in Fig. 3. The model was equipped with elevons that could be deflected by means of hinge-line brackets and replaceable body flaps machined for different deflections. Because the present study was secondary to a test being conducted with this model at the same time, only the body flap with zero deflection was available for modification. Note that the body flap is the current shuttle geometry, not the preferred rectangular geometry discussed in the concept section. A single controller representing a 90-deg deflection was fabricated and attached to the existing body-flap underside with machine screws. A drawing of the controller is shown in Fig. 4, and a photograph of the model underside with the controller attached is shown in Fig. 5. The deflected controller is triangular in planform with a leading-edge sweep of 60 deg. The planform area is 0.56% of the wing reference area.

Tests

The force and moment tests were conducted for an angle-of-attack range of 20–40 deg at zero sideslip angle. The model was tested with the body flap alone (at zero deflection) and with the controller representing 90-deg deflection attached, at a unit Reynolds number of 2.2×10^6 per foot (0.66×10^6, based on the wing mean aerodynamic chord).

Instrumentation

The force and moment measurements were obtained from a six-component, water-cooled, internally mounted strain-gauge balance. Balance temperatures were monitored by two thermocouples installed in the surrounding water jacket. The opportunity to conduct repeat runs was not available for this test, and so determination of the uncertainties was limited to the balance uncertainties. The calibration accuracy is 0.5% of the design load rating for each of the six components, and the balance-related uncertainties in the coefficients are as follows: C_N, ±0.0095; C_A, ±0.0019; C_Y, ±0.00096; C_m, ±0.0016; C_n, ±0.00014; and C_l, ±0.00027. The moment



Reference data	Full scale	.0075 scale
Area	2690.0 ft^2	0.1513
Length	1290.3 in.	9.677
Span	936.68in.	7.025
$\bar{c}$	474.8 in.	3.561
Aspect ratio	2.265	2.265
Wing sweep	45	45
Vertical tall area	413.25 ft^2	0.0232
Vertical tall aspect ratio	1.675	1.675

Fig. 3 Three-view sketch of the Orbiter configuration used in the investigation showing the full- and 0.0075-scale model dimensions (dimensions given in inches).

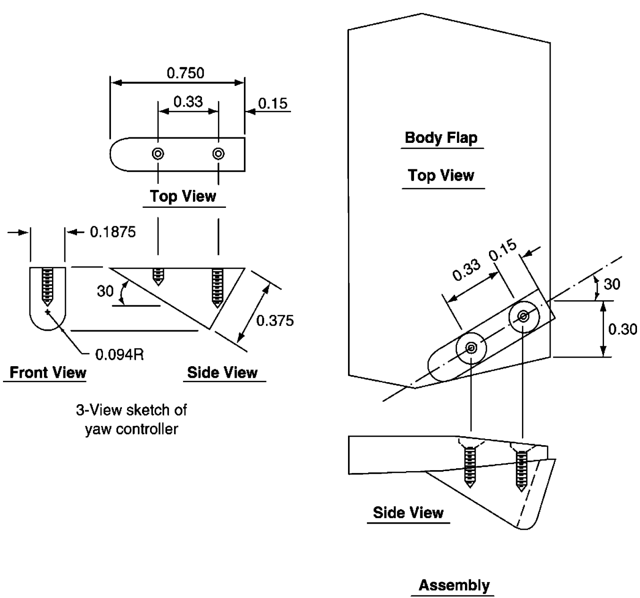


Fig. 4 Sketch of yaw controller as built and tested, showing the pertinent dimensions and the arrangement when assembled (dimensions given in inches).

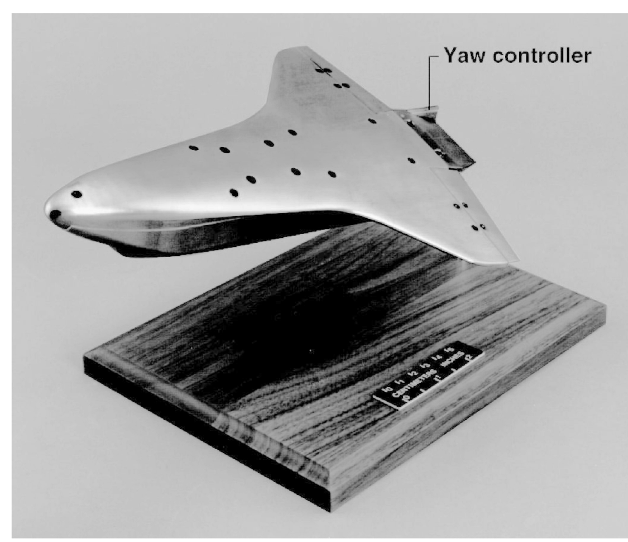


Fig. 5 Photograph of the model with the yaw controller attached to the body flap.

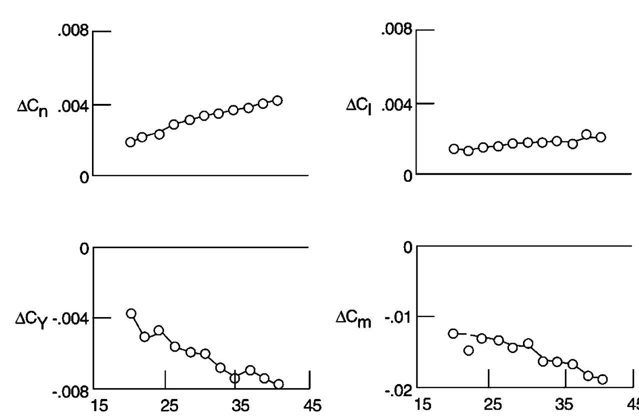


Fig. 6 Variation of the incremental force and moment coefficients with angle of attack.

coefficient uncertainties include the uncertainties in the force coefficients used in the moment transfer equations. The force and moment data were corrected for weight tares, and angle of attack was corrected for sting and balance deflection under load. An oil-flow visualization of the lower surface of the model with the controller attached at $\alpha = 40$ deg was recorded with a conventional camera.

Force and Moment Test Results

The force and moment data are presented in Fig. 6 in the form of incremental coefficients resulting from the yaw controller at 90-deg deflection. Installation of the yaw controller deflected 90 deg produced positive yawing-moment and negative side-force increments that increased with increasing angle of attack. A simple calculation of the pressure coefficient on the windward surface of the controller based on ΔC_Y at $\alpha = 40$ deg, assuming that the load is evenly distributed on the controller surface, produced a value of $C_p = 1.623$, or

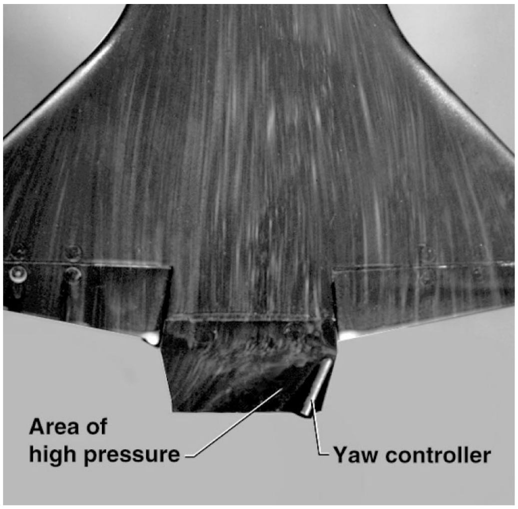


Fig. 7 Surface oil-flow pattern on the bottom of the model with the controller installed.

about 89% of the stagnation pressure on the nose of the model, which indicates that the controller is highly loaded. The sizable negative pitching-moment coefficient also indicates an increase in pressure on the lower surface of the model in the region of the body flap. This is supported by the oil-flow visualization in Fig. 7, which shows a line of separation that originates at the apex of the controller and sweeps across the body flap to the trailing edge of the right half of the flap. The turning of the flow ahead of this line indicates a higher pressure in the region aft of the line. Regions of high surface pressure usually have high surface heating at hypersonic conditions. The rolling-moment coefficient produced by deflection of the controller is about half of the yawing moment (Fig. 6) and is in a favorable direction (positive). This relationship between the yawing and rolling moments shows that the control, if sufficiently effective, could produce a coordinated turn when used in conjunction with the ailerons to modulate the rolling moment.

Although the increment in pitching moment produced by the controller is sizable ($\Delta C_m = 0.0189$ at $\alpha = 40$ deg, where the high-altitude bank maneuvers occur) and causes the vehicle to be out of trim, the data of Ref. 5 show that it can be trimmed out with −5-deg elevon deflection. A great deal of the moment can be trimmed with the body flap itself, but the level of trim available depends on the initial body-flap deflection. In the present case, with the body flap initially at zero deflection, the full-up position ($\delta_{BF} = -11.7$ deg) would produce a ΔC_m of 0.015. Unpublished results with a wing-body model having a similar body-flap yaw controller deflected 90 deg showed that deflection of the body flap to −10 deg reduced the controller effectiveness linearly from 39 to 8% of the effectiveness at zero body-flap deflection between $\alpha = 20$ and 40 deg, respectively.

Analysis and Discussion

The aerodynamic data have shown that the yaw controller produces a yawing moment without adverse effects on the other aerodynamic parameters. It has not been established that the control has sufficient effectiveness to adequately maneuver the vehicle. A first-order estimate of this can be obtained by directly comparing the control output to that of the side-firing RCS thrusters. A single yaw thruster produces a vacuum thrust of about 870 lbf, which remains nearly constant to an altitude of 100,000 ft. The output of the yaw controller varies with altitude and increases as altitude decreases (increasing density). At the altitude of Mach 18 (209,000 ft), the yawing moment produced by the yaw controller is about 1.77 times that of a single thruster. This is based on the assumption that the yawing-moment coefficient obtained from the Mach 10 test is applicable to Mach 18 flight. This assumption is justified by the fact that the effectiveness of the body flap (to which the yaw controller is attached) is unchanged between Mach 20 and Mach 8 at $\alpha = 40$ deg (Ref. 5). This may warrant more study, because the shock structures on the controller would be different than on the body flap alone, and it may be more dependent on flow-chemistry effects. However, most of the Orbiter bank maneuvers were initiated with the part-time use of all four side-firing thrusters to provide acceleration in yaw. Therefore, at the altitude of Mach 18, the yaw controller is about 44% as effective as the four side-firing thrusters. At the altitude of Mach 10, the yaw controller is about 66% as effective as the four thrusters.

The yaw controller can provide the same angular momentum as the side thrusters, but it would obviously take a longer time due to the lower effectiveness. This increased time can be problematic at the higher Mach numbers, where the dynamic pressure is low and the aerodynamic heating rate on the controller is at a maximum.

The Orbiter bank maneuver about the velocity vector requires a combination of yaw and roll about the respective body axes to maintain the desired angle of attack during the maneuver. The yaw thrusters produce a yaw rate and a small sideslip angle β. This sideslip angle generates a rolling moment in the direction of the turn because of the favorable effective dihedral parameter $C_{l\beta}$. The ailerons are used for turn coordination and directional trim.

To establish the feasibility of making a bank maneuver using only aerodynamic controls, an analysis was conducted with a combination of the aerodynamic yaw controller and the ailerons. The STS-1 entry flight data[6] were chosen for the analysis. The entry trajectory showing bank maneuvers and angle of attack vs time[6] is presented in Fig. 8. As in all Orbiter entries, five bank maneuvers are made before reaching the landing area. The first bank maneuver is made where the dynamic pressure is low (12 psf in STS-1) and a bank maneuver initiation with the yaw controller at this point would require a considerable length of time. This maneuver was not executed in the nominal way in STS-1, and there would be no way to compare the results. The second bank maneuver at Mach 18 was nominal and was chosen for the present analysis. The altitude at this point was 209,000 ft, the relative velocity was 18,477 ft/s, the dynamic pressure was 70.2 lb/ft^2, and the angle of attack was 40 deg. The wind-tunnel data were referenced to a nominal c.g. position of 65% of the reference body length and the STS-1 flight c.g. was 66.5%. The resulting shorter moment arm for flight required an adjustment in the yaw-controller effectiveness, $\partial C_n/\partial_Y$, $\partial C_m/\partial_Y$, and in the value of $C^5_{n\beta}$.

The vehicle and trajectory parameters and the aerodynamic coefficients used in the analysis are given in Table 1. The aerodynamic

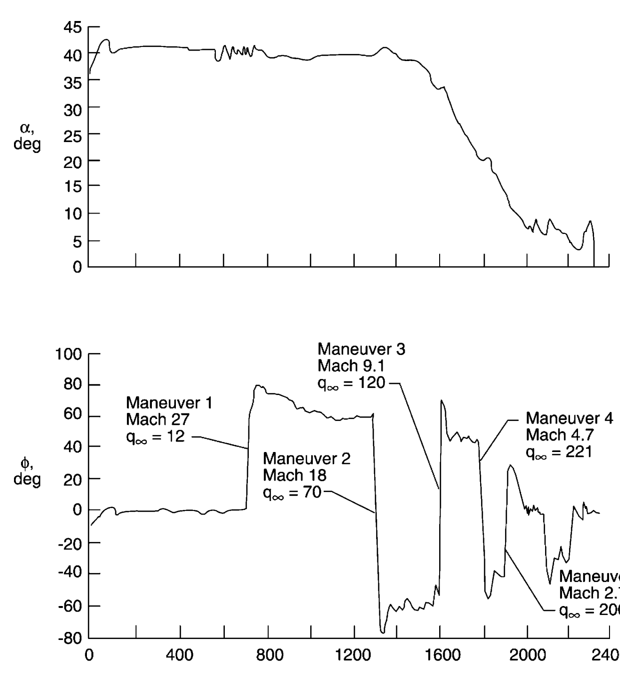


Fig. 8 STS-1 entry showing the bank maneuvers and angle of attack vs time.[6]

Table 1 Variables used in the three-dimensional analysis

Parameter	Value
Aerodynamic	
$\Delta C_l (\delta_Y = 90 \text{ deg})$	−0.00199
$\Delta C_m (\delta_Y = 90 \text{ deg})$	−0.0184
$\Delta C_n (\delta_Y = 90 \text{ deg})$	−0.003902
$\Delta C_Y (\delta_Y = 90 \text{ deg})$	0.00786
$C_{m\delta e}$	−0.0034
$C_{l\delta a}$	0.00143
$C_{l\beta}$	−0.0017
$C_{n\delta a}$	−0.00041
$C_{n\beta}$	−0.00161
$C_{Y\delta a}$	0.00043
$C_{Y\beta}$	−0.0052
Vehicle	
Wing area	2,690.0 ft^2
Wingspan	78.1 ft
Weight	195,942.7 lb
I_{XX}	878,620.8 slug · ft^2
I_{YY}	7,160,504.1 slug · ft^2
Body-flap deflection	0.0 deg
Elevon deflection	0.0 deg
Trajectory	
Altitude	209,000.0 ft
Velocity	18,477.0 ft/s
Mach number	18.0
Dynamic pressure	70.27 lb/ft^2
α	40.0 deg
β	0.0 deg

data consist of the yaw-controller increments taken from Fig. 6 at $\alpha = 40$ deg (with the signs reversed to match the maneuver direction), and the Orbiter vehicle stability and control parameters taken from the aerodynamic data book,[5] with $\partial C_n/\partial_Y$, $\partial C_m/\partial_Y$, and $C_{n\beta}$ adjusted for the c.g. location of that of STS-1.

The analysis consisted of using the data of Table 1 in the lateral three-degree-of-freedom equations of motion in yaw, roll, and sideslip. It was assumed that the yaw controller takes 2 s to fully deflect from 0 to 90 deg, 2 s to retract to 0. Because the data are only available for 90-deg deflection, the transient aerodynamics were modeled by modifying the coefficient values at 90 deg by the sine squared of the intermediate deflection angle. It was mentioned earlier that the rolling-moment coefficient was about one-half the yawing-moment coefficient for the deflected yaw controller. However, the yaw moment of inertia is 8.15 times the roll moment of inertia; therefore, when the controller is deflected, the vehicle will accelerate in roll four times faster than in yaw. Because of this, it was necessary to modulate the roll rate by deflecting the ailerons. In making a bank maneuver about the velocity vector at a constant angle of attack, the vehicle must maintain a constant ratio of roll to yaw that is a function of angle of attack. At a 40-deg angle of attack, that ratio is 1.192. The aileron deflection was calculated to maintain this ratio of roll to yaw angular velocity during the entry into the bank maneuver. The elevon deflection required to maintain longitudinal trim during the maneuver was calculated for the purpose of determining the value of the aileron derivative at that particular elevon deflection, but it had no bearing on the calculation of the lateral angular motions. The values of the aileron derivatives were adjusted for an average elevon deflection between 0 and −5 deg. The equations of motion were programmed in an open-loop mode; therefore, several cases were run to obtain convergence on a roll rate equivalent to the final roll rate of the flight case (approximately −4 deg/s). In each case, the elapsed time for the controller at 90-deg deflection was varied until the desired roll rate was obtained. The calculation of the motions was a simple direct summation process over time intervals of 0.10 s.

The results of the analytical calculations are compared to the flight case in Fig. 9, in which the initial entry into the Mach 18 bank reversal (maneuver 2, Fig. 8) is presented as a function of time. This figure shows the first 8 s of the maneuver, from initiation of the motion to where the steady-state roll rate is established. In the total maneuver, these steady-state motions are maintained until the desired bank angle is established (about 30 s), and the reverse process takes place to arrest the motion. The curves on the left-hand side show control actions and those on the right-hand side show the resulting attitude and motions. In the flight case (solid line), the left-hand-side yaw thrusters are fired (upper left in the figure) and the ailerons move to counter the initial adverse roll from the thrusters. Note that all four thrusters are firing most of the time. Only at the end does the number drop to three, and then two. Sideslip angle β builds up and the favorable dihedral effect (negative value of $C_{l\beta}$) causes the vehicle to roll. The roll rate builds up to an overshoot and the aileron reverses to moderate this. The roll rate is established in about 5 s.

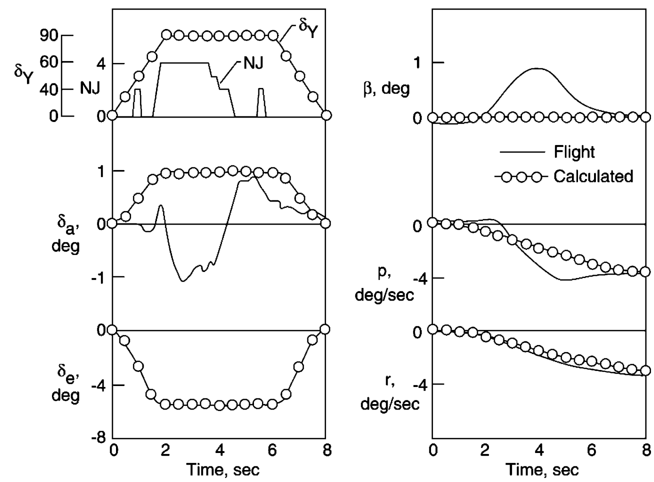


Fig. 9 Comparison between calculations for the initiation of the STS-1 entry bank reversal at Mach 18 using the aerodynamic yaw controller with the actual flight maneuver ($H = 209{,}000$ ft; $V = 18{,}477$ ft/s; $q_\infty = 70.26$ psf; $\alpha = 40$ deg).

The yaw controller (open circles), also shown in the upper left of Fig. 9, is deflected to 90 deg and remains there for 4 s and then returns to 0 deg, for a total elapsed time of 8 s. The aileron deflects positively to about 1 deg to modulate the excess roll moment generated by the yaw controller. The positive aileron is desirable because negative $C_{n\delta a}$ reinforces the yawing moment of the controller. On the right-hand side, the roll rate builds up to nearly the same as the flight roll rate, and the yaw rate builds up proportionally. Sideslip angle β remains very nearly zero (maximum value is 0.024 deg), which confirms that the ratio of proportionality between the yaw and roll rates is correct, and the angle of attack will be maintained close to the desired 40 deg. The sequence shown in Fig 9 shows that the yaw controller, in conjunction with the ailerons, can initiate a bank reversal comparable to the RCS/aileron combination with the advantage that no RCS propellant was expended. However, the yaw controller would result in additional weight and complexity. At Mach 18, the time required to initiate the maneuver was longer by 3 s, primarily because of the time allotted for deflecting and retracting the controller. This time allotment was arbitrary; it could take longer. It can only be established with a detailed design study of such a system. Succeeding bank maneuvers would require less time to initiate because dynamic pressure increases as entry altitudes decrease. Using the RCS to conduct this maneuver at Mach 18, including the initiation and termination, is estimated to require approximately 66 lb of propellant. The yaw controller, if used for four bank maneuvers, would save approximately 264 lb of RCS propellant.

Conclusions

The results of a limited wind-tunnel investigation of the effectiveness of an aerodynamic yaw controller at Mach 10 mounted on the lower surface of a Space Shuttle Orbiter model body flap indicate that the controller was effective in producing sufficient yawing moment and produced a favorable rolling moment. The effectiveness of the controller decreased as angle of attack decreased from 40 to 20 deg. The controller produced a nose-down pitching moment that could be compensated for by −5-deg elevon deflection or a combination elevon and body-flap deflection.

Assuming that the Mach 10 wind-tunnel data can be applied at Mach 18 flight conditions, an analysis of the controller as applied to the STS-1 bank reversal at Mach 18 showed that the controller was as effective as the RCS thrusters in initiating the maneuver, although more time was required. The use of the yaw controller is estimated to save approximately 264 lb of RCS propellant.

Additional wind-tunnel tests are needed to determine the effects of Mach number, angle of attack, body-flap deflection, boundary-layer transition, and high-temperature phenomena on the controller characteristics. The aerodynamic heating of the controller and the body flap needs to be determined before the applicability of the control concept to lifting entry vehicles can be established. It is noted that the use of the yaw controller on the Space Shuttle Orbiter would result in an increase in vehicle dry weight and an aft c.g. movement; thus, the benefits would have to be assessed against this. However, the present limited study has shown that the yaw-controller concept is potentially useful for lifting-entry vehicle configurations such as the Space Shuttle Orbiter, the HL-20, and advanced lifting winged space vehicle concepts.

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