Numerical Analysis of Aerodynamics and Flight Trajectory of JAXA's High-Mach Integrated Control Experiment (HIMICO)

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The aerodynamic characteristics of a small-size hypersonic experimental aircraft called HIMICO are numerically simulated using CFD. A wide range of angles of attack and side-slip angles in Mach-5 flows are investigated, and the results are compared with wind-tunnel tests (WTT). Dynamic stability derivatives are also estimated using CFD. The flight trajectories are then calculated based on the aerodynamic coefficients obtained using CFD. The effects of aerodynamic damping due to the dynamic stability derivatives are large, especially on the attitude of the aircraft with an initial roll/yaw angle deviating from the nominal. Even so, the important criteria for the engine test are satisfied by both results under the assumed initial conditions. Validation of the simulation methods developed for designing hypersonic aircrafts was confirmed.

Key Words: Hypersonic Aircraft, CFD, Flight Trajectory

Nomenclature

c_p	: pressure coefficient
C_x	: aerodynamic force/moment coefficient (subscript x defined below)
F_n	: flux vector normal to a control volume surface
Q	: conservative flow variable vector
U	: freestream or flight velocity
s	: source term vector
α	: angle of attack, rad
β	: side-slip angle, rad
θ	: pitch angle, rad
ϕ	: roll angle, rad
ψ	: yaw angle, rad

Subscripts

D	: drag
L	: lift
l	: roll
m	: pitch
n	: yaw
p	: roll-angular rate
q	: pitch-angular rate
r	: yaw-angular rate
Y	: side force

1. Introduction

Hypersonic passenger aircraft that reduce trans-Pacific

flight time by a factor of five are anticipated, and are being explored as a future form of transport to be realized. JAXA and collaborative universities are currently developing a small experimental plane named ‘High-Mach Integrated Control Experimental Aircraft’ (HIMICO) that will fly at Mach 5. The principal aim is to demonstrate a new hypersonic engine and control the airframe attitude in an actual flight environment. Achieving this is regarded as the first of three stages required to attain hypersonic civil transportation.¹⁾ The latest plan for the flight experiment is further split into two stages: the first one, named HIMICO-#1, is a smaller-size aircraft that will fly without testing the engine to observe stability and controllability; and the second one, named HIMICO-#2, will use the same flight sequence with engine operating.

The overall activities for the research and development of HIMICO have been described in a paper presented at the 32nd ISTS by one of the coauthors of this article.²⁾ Specific emphasis of this study is on the accuracy of the external flow CFD around HIMICO-#2 and evaluation of the flight trajectory calculated with the aerodynamic coefficients, as well as the dynamic stability derivatives obtained using CFD.

2. HIMICO-#2 Flight-Experiment Sequence and Scope of the Present Study

Figure 1 shows a schematic of the HIMICO flight experiment. The aircraft is stored in the nose of a S-520 rocket and climbs to its highest altitude, close to 90 km, after launch. In the descent path, HIMICO will separate from the rocket at the altitude of 85 km, at which the dynamic pressure of the airflow will be almost zero (estimated as small as 10 Pa).

Fig. 1. Flight plan of HIMICO-#2.

Figures 2(a) and 2(b) respectively show variations of altitude and dynamic pressure over time after the launch. They are planned based on a simplified aerodynamic analysis of the HIMICO without engine operation and using the Local Surface Inclination (LSI) method,³⁾ which employs a Newtonian flow model. It is quite important for stable flight and to properly capture the airflow into the engine to accurately predict the aerodynamic performance of the aircraft. The objective of the present study is therefore to carry out CFD, solving Navier-Stokes equations in the flight range where the dynamic pressure significantly increases after around 250 s, as shown in Fig. 2(b). The following 60 s includes the pull-up maneuver and combustion testing of the engine at the target dynamic pressure of 50 kPa.

(a) Flight altitude vs. time

(b) Dynamic pressure vs. time

Fig. 2. Nominal flight trajectory and conditions.

3. Flow Simulation Method

3.1. Governing equations for steady-state simulations

The compressible Reynolds-averaged Navier-Stokes (RANS) equations are the governing equations for the numerical simulations. The Spalart-Allmaras (SA) turbulence model is used to determine the eddy viscosity added to the laminar (molecular) viscosity. Considering the quadratic

constitutive relation (QCR),⁴⁾ the modified model is actually used and the specific version of the model is SA-noft2-R-QCR2000, following the notation given in the turbulence modeling resource.⁵⁾ The system of equations is written in the integral form as follows,

$$\frac{\partial}{\partial t} \int_{\Omega} Q dV + \oint_{\partial\Omega} F_n dS = \int_{\Omega} s dV, \quad (1)$$

where, Q is a conservative variable vector, Ω is a control volume (CV), t is the time, F_n is a flux vector in the normal direction to the CV boundary $\partial\Omega$, and s is a source term vector which has non-zero elements for the SA model.

3.2. Numerical methods for steady-state simulations

The governing equations are numerically solved using the in-house CFD code UM2⁶⁾ standing for unstructured-mixed meshes. A brief description of the code is given below.

The spatial discretization is the cell-vertex finite-volume method and second-order accuracy is achieved through linear reconstruction of the primitive variables. The slope limiter by Venkatakrishnan⁷⁾ is used to stably calculate strong shock waves in the hypersonic flows. Inviscid flux is calculated using the high-resolution upwind scheme SHUS⁸⁾ and viscous flux is equivalent to the central scheme. For the time marching to obtain solution convergence, the LU-SGS implicit method is used and the source term in the turbulence model is also treated implicitly.

3.3. Simulation method for dynamic stability derivatives

In addition to steady flow analyses, flows around the aircraft in small-amplitude forced oscillations about each axis are simulated to obtain the dynamic stability derivatives. In order to efficiently find such a periodic unsteady solution in a short time, we use the time spectral method,⁹⁾ applying time Fourier series expansion of the flow variables. New equations for the expansion coefficients are derived by substituting the Fourier series into Eq. (1). It does not mean a completely new CFD code is necessary, but the existing code needs only minor modifications since the same numerical fluxes are computed and the same matrix-inversion (LU-SGS) is used to iterate the equations to convergence. For details of the method, see Ref. 9).

4. Aircraft Configuration and Computation Conditions

Figure 3 shows the top and side views of HIMICO-#2. The total length of the body is 1.534 m and the span length of the wing is 0.37 m for the actual flight experiment, which has

Fig. 3. Top and side view of HIMICO-#2.

been determined to be stored in a S-520 rocket. The diameter of the fuselage is 0.18 m and the semi-apex angle of the nose cone is 9.13 deg. As for the main wing, the leading-edge sweepback angle is 77.6 deg, the root chord length is 0.8 m, and the tip chord length is 0.212 m. A 25% scaled model is used in the reference WTT conducted in a hypersonic wind tunnel with 0.5x0.5 m² test sectional area at JAXA.¹⁰⁾

The flow conditions calculated are shown in Table 1. The Reynolds number of the flow, based on the total length of the body, is 6.1x10⁶, which corresponds to the actual flight experiment.

Table 1. Flow conditions at Mach 5.

Fixed angle [deg]	Variable angles (sweep) [deg]
$\beta=0, 5, 10$	$\alpha=-35\sim35$ (every 5 deg)
$\alpha=0$	$\beta=0\sim30$ (every 5 deg)

5. Flow Simulations Results

5.1. Computational grids

Figure 4 shows computational grids around the aircraft. They are generated by the HexaGrid automatic grid generator,¹¹⁾ developed by JAXA. The grid is dominantly composed of hexahedron cells, and the total number of grid points is 4,064,723 in most computations. As will be stated in a later subsection, finer grids with roughly twice the number of grid points and some other grids are also used.

Fig. 4. Computational grids for CFD.

5.2. Aerodynamic characteristics

The aerodynamic coefficients and attitude angles used in trajectory simulations in later sections follow the same convention for the aircraft dynamics.

Figure 5(a) shows comparisons of simulated longitudinal characteristics with the experiments (WTT). The C_D agrees well with the WTT at all angles of attack. The C_L and C_m also show reasonable agreement, but discrepancy from the WTT gradually increases at angles higher than $\alpha>20$. One of the possible reasons is studied below in this subsection. As for C_m , two positions of the moment center, 57% and 60% station of the total length of the body, are assumed and they are regarded as the center of gravity (CG). The 60% station is not a proper position for CG due to the statically longitudinal instability ($dC_m/d\alpha>0$), while the 57% station is a proper position. The position of the aerodynamic center (AC), at which C_m is constant and independent of α , can be calculated

Fig. 5. Longitudinal and lateral directional characteristics.

using the following formula,

$$C_{m,0}(\alpha) = C_{m,AC}(\alpha) - (x_{AC}/L) \cdot C_L(\alpha). \quad (2)$$

The estimated AC is a 56% station. The static margin, $x_{CG}-x_{AC}$, is quite small and the position of CG should be carefully determined by arranging the internal layout of the instruments. Figure 5(a) contains the results using a different CFD code, FaSTAR,¹²⁾ developed by JAXA. The same SA-noft2-R-QCR2000 turbulence model is selected for FaSTAR as well. The results in Fig. 5 (a) show that the results using both CFD codes are very close to each other on the same computational grids.

Figure 5(b) shows lateral directional characteristics. Dependencies of C_Y, C_L , and C_n on β are very well reproduced using CFD. It again shows the sensitivities to the position of CG. The 60% CG shows statically directional instability ($dC_n/d\beta<0$), while the 57% station results in clear stability.

Figures 6(a) and 6(b) show the results of α -sweep at a fixed β of 5 deg. Only 57% CG is considered as the moment center. The agreements of the longitudinal coefficients with the WTT in Fig. 6(a) are rather good. The lateral directional coefficients in Fig. 6(b) show discrepancies at angles of large absolute values. The tendency of $dC_n/d\alpha<0$ at a positive sideslip angle of $\beta=5$ is common for CFD and the WTT, and both show C_n becomes negative at $\alpha>5$ deg, which results in directional instability under these conditions. To overcome the problem, it is planned that the aircraft keeps negative α (inverted flight) from separation from the S-520 rocket until the end of the pull-up maneuver (Fig. 2), and then performs a

180-degree roll motion to keep a proper positive α before the engine test starts.²⁾

Figure 7 includes only CFD results for the same Mach number and flow angles as Fig. 5(a) to show the three aspects described below and listed in Table 2.

Fig. 6. Aerodynamic characteristics with $\beta=5$.

Fig. 7. Effects of Reynolds number, intake configuration and the grid resolution.

Table 2. Numerical aspects compared in Fig. 7.

Cases (Legend in Fig. 7)	Intake front configuration	Reynolds number ($\times 10^6$)	Total number of grid points
WTT_Re	Closed	1.1	3,673,488
Flight_Re	Closed	6.1	4,064,723
Flow_thru	Open	6.1	4,511,600
Fine grid	Closed	6.1	9,141,371

The first aspect examined was to compare the engine air-intake conditions. In Figs. 5 and 6, the intake was closed as in the WTT, which corresponds to the ‘unstarted’ conditions of the hyper/supersonic intakes. On the other hand, flow-through conditions from the intake to exit without the engine are considered, although the internal shape is simplified to a constant-area rectangular duct. The aerodynamic forces/moments for the actual flight are considered to be within the two extreme cases. Reflections of shock waves in the duct can be seen in the pressure contour plots at the cross-section of $y=0$ in Fig. 8, but these flow features have little influence on the overall forces/moments, as seen in Fig. 7.

Fig. 8. Flow-through configuration of the intake.

The second aspect we checked was the effect of Reynolds number between the conditions for WTT and the actual flight experiment. The number of grid points is about 10% less for the WTT Reynolds number since the minimum cell width normal to the wall is larger. The grid resolutions are identical in terms of space. The results of the two Reynolds numbers almost coincide with each other. But it must be noted that the quantitative discussion of the Reynolds number effects is not possible using the RANS CFD.

The final aspect was to see the effect of grid resolution, especially near the main wing where leading-edge separation

(a) Base grid (b) Fine grid

(c) c_p distributions at $x/L=0.8$ cross-section

Fig. 9. Effect of grid resolution on the vortex over the wing.

vortices exist. Using the HexaGrid refinement box function, local grids two-times finer in all directions only near the main wing were prepared. Two cases of high angles, $\alpha=20$ and 30 at $\beta=0$, were run. Figures 9(a) and 9(b) show the Mach-number contour plots at $\alpha=20$ and the grid point distribution at the $x/L=0.8$ cross-section. Figure 9(c) shows comparisons of the c_p plots on the body at the same station. Little change in the negative c_p on the upper surface of the wing can be seen in these plots. Additionally, the improvements in C_L and C_m were quite small (about 2% difference from the original grid). Possible reasons for the differences at high α are inaccurate prediction of the eddy-viscosity turbulence model, or an insufficient grid resolution for the complex geometry near the engine air-intake.

CFD simulations at Mach 3 were also carried out for the flight trajectory simulations, and the Mach-number effects are compared in Fig. 10. The slopes of C_L and C_m are both higher than in the case of Mach 5, thus indicating deterioration in the aerodynamic performance at higher Mach numbers.

Fig. 10. Effects of flight Mach number at $M=3$ and 5 .

5.3. Predictions of dynamic stability derivatives

Dynamic stability derivatives are important for predicting flight trajectories and designing an aircraft's control system. The derivatives are calculated using the CFD from the unsteady responses of the aerodynamic moments caused by the forced oscillation of the aircraft. The damping in pitch $C_{m,q}$, roll $C_{l,p}$ and yaw $C_{n,r}$ are separately obtained using the forced oscillations around respective axes. The numerical method was validated in Ref. 13), and a brief overview is given below.

For example, the variation of C_m due to a forced pitching oscillation about a mean angle of attack α_M is approximated as a linear function of α , $\dot{\alpha}$ and q as follows,

$$C_m = C_{m0} + C_{m_\alpha} \Delta\alpha + C_{m_{\dot{\alpha}}} \frac{\dot{\alpha}\bar{c}}{2U} + C_{m_q} \frac{q\bar{c}}{2U}, \quad (3)$$

where, derivatives with respect to the angular velocity are nondimensionalized by the freestream velocity and half of the reference length $\bar{c}$. For the pitching oscillation in a horizontal freestream, $\theta = \alpha = \alpha_M + \alpha_A \sin(\omega t)$, and then Eq. (3) becomes

$$C_m = C_{m0} + C_{m_\alpha} \alpha_A \sin(\omega t) + (C_{m_{\dot{\alpha}}} + C_{m_q}) \frac{\omega\bar{c}}{2U} \alpha_A \cos(\omega t). \quad (4)$$

In this study, $\bar{c}$ is 1.5 times the wingspan and $\alpha_A=2$ deg. The

reduced frequency is $\omega\bar{c}/2U=0.025$.

As a result of the time spectral method, the first term and remaining terms in the right-hand-side of Eq. (4) are obtained as the zeroth- and first-harmonic component of the Fourier series of C_m , respectively. The derivative $C_{m_{\dot{\alpha}}}$ is separately obtained from the forced linear (heaving) oscillation, but it turns out that it is much smaller than C_{m_q} .

Similarly, the roll-damping sum and yaw-damping sum are obtained based on the following formulae,¹⁴⁾

$$C_l = C_{l0} + C_{l_\beta} \Delta\beta + (C_{l_p} + C_{l_\beta} \sin \alpha) \frac{p\bar{c}}{2U}, \quad (5)$$

$$C_n = C_{n0} + C_{n_\beta} \Delta\beta + (C_{n_r} - C_{n_\beta} \cos \alpha) \frac{r\bar{c}}{2U}. \quad (6)$$

Figure 11 shows the damping calculated at Mach 5 and $\beta=0$. The negative coefficient values mean positive dynamic stability. The roll damping is small due to the slender body of HIMICO-#2. The yaw damping is large due to the relatively large vertical tail and it shows stronger α -dependency than roll and pitch. Negative α results in stronger dynamic stability in yaw.

Fig. 11. Dynamic stability coefficients at $M=5$ and $\beta=0$.

6. Flight Trajectory Simulations

The flight trajectories of HIMICO-#2 are calculated by solving the six-degrees-of-freedom equations of motion. There can be various uncertainties in the simulations; for example, the wind, misalignment of the CG, or initial deviations from nominal conditions of the aircraft attitude, motion. Uncertainties in the aerodynamic coefficients can have a significant effect on the trajectory. The aerodynamic database obtained using the steady and unsteady CFDs are both used and compared to see if the success criteria of the flight experiment are fulfilled. Those uncertainties will be compensated during actual flight by controlling the elevon and rudder, which is not considered in the present paper, but the following simulations investigate the basic performance of the HIMICO-#2 without controls. The mass, moment of inertia, and CG are shown in Table 3.

Table 3. HIMICO-#2 mass properties.

Mass [kg]	Moment of inertia (I_x, I_y, I_z) [kgm ²]	CG (x, y, z)
41.369	(0.235, 6.762, 6.736)	(0.57L, 0, 0) ($L=1.534$ [m])

6.1. Nominal conditions

Trajectory calculations start when dynamic pressure rapidly rises after launching the S-520 rocket, at 250 s in Fig. 2. Initial conditions assumed are an altitude of 48 km, flight Mach number of 5, pitch angle of -17 deg and flight-path angle of -33 deg. The simulation continues for 60 s of the flight. Figures 12(a)-12(f) show comparisons of the flight trajectories in the vertical plane with and without dynamic stability derivatives. The aerodynamic coefficients of CFD are interpolated/extrapolated between the results of two Mach numbers, 3 and 5. Figures 12(a)-12(f) are altitude, dynamic pressure, Mach number, pitch angle, angle of attack, and down range, respectively.

Mach numbers in Fig. 12(c) are in the proper range for the CFD data to be used. Approximately 280 s after launch, the dynamic pressure in Fig. 12(b) reaches the engine test condition of 50 kPa. The pitch angle and angle of attack in Figs. 12(d) and 12(e) show the pull-up maneuver is achieved by itself without elevon control and converges to a proper angle of attack for the ideal initial conditions. If engine thrust is added, engine testing with a duration of 20-30 s is expected. As for the effect of pitch damping, little difference can be seen in Figs. 12(a)-12(c) and 12(f). On the other hand, the oscillations in pitch and angle of attack are fast damped with the dynamic stability derivatives in Figs. 12(d) and 12(e), thus providing more stable air to the engine.

6.2. Initial misalignment of attitude angles

As possible deviations from the ideal case, a roll angle and yaw angle are given as the initial conditions. Specified angles are $\phi=1$ and $\psi=1$, respectively. As discussed in Section 4.2, inverted flight with the vertical tail downward is currently planned at the initial phase before the engine test in order to avoid directional instability at $\alpha>0$. However, in our trajectory calculation, flight conditions cannot keep the altitude and Mach number since the elevon is not taken into account in the aerodynamics of the present study. The roll/yaw deviations are then added to the initial conditions of Section 5.1 as a trial. Trajectories with and without the dynamic stability derivatives are again compared. Figures 13(a)-13(f) are altitude, dynamic pressure, side-slip angle, roll angle, yaw angle, and cross-range, respectively. Figures 13(a) and 13(b) include the results with damping only because of the small difference, as in Figs. 12(a) and 12(b). The figures also show little effect of small misalignments on the altitude and dynamic pressure. However, aerodynamic damping has a significant impact on the angles of side-slip, roll, yaw and cross-range in Figs. 13(c)-13(f), respectively. For both misalignments of roll and yaw, β converges to zero with damping considered, before the engine starts, or before the dynamic pressure reaches 50 kPa. The aircraft attitude also differs with the damping, and both the roll and yaw angles converge to a constant value as shown in Figs. 13(d) and 13(e). The cross-range in Fig. 13(f) becomes smaller as a result, which is especially important to suppress the dispersion of the flight range in the experiment.

7. Conclusion

This paper examined the aerodynamic characteristics of the

HIMICO-#2 in detail, and the numerical accuracies of CFD are discussed through comparisons with WTT. Predictions at low and moderate α are good for both cases with and without β , but the discrepancies at high α remained even with the finer computational grid. Dynamic stability derivatives were also calculated using CFD from the forced oscillations around each body axis. As for the flight-trajectory simulations, it has been shown that ideal initial conditions will fulfill the success criteria for engine testing even without a control surface. The trajectory simulation further showed that small deviations from the ideal conditions are allowed.

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References

- 1) Taguchi, H., Kobayashi, H., Kojima, T., Hongoh, M., Sato, T., and Tsuchiya, T., and Tsue, M.: Flight Experiment of Hypersonic Pre-Cooled Turbojet Engine, Proceedings of 59th Space Science and Technology Conference, Kagoshima, Japan, JSASS-2015-4450, 2015 (in Japanese).
- 2) Sato, T., Taguchi, H., Kojima, T., Tsuchiya, T., Tsue M., Nakaya, S., Matsuo, A., Tezuka, A., Fujikawa, T., and Miyaji, K.: Program of High Mach Integrated Control Experiment "HIMICO" using S-520 Sounding Rocket, 32nd International Symposium on Space Technology and Science, Fukui, Japan, 2019-m-01, 2019.
- 3) Tsuchiya, T., Takenaka, Y., and Taguchi, H.: Multidisciplinary Design Optimization for Hypersonic Experimental Vehicle, *AIAA J.*, **45**, 7 (2007), pp. 1655-1662.
- 4) Spalart, P. R.: Strategies for Turbulence Modeling and Simulation, *International J. Heat and Fluid Flow*, **21** (2000), pp. 252-263.
- 5) Turbulence Modeling Resource, <https://turbmodels.larc.nasa.gov/> (accessed April 1, 2019).
- 6) Nakamura, K. and Miyaji, K.: RANS Simulations of NASA-CRM by the Finite-volume Method with the SST Turbulence Model, *Koku-Uchu-Gijyutsu (Aerospace Technology Japan)*, **17** (2018), pp. 219-225 (in Japanese).
- 7) Venkatakrishnan, V.: Convergence to Steady State Solutions for the Euler Equations on Unstructured Grids with Limiters, *J. Computational Physics*, **118**, 1 (1995), pp. 120-130.
- 8) Shima, E. and Jounouchi, T.: Role of CFD in Aeronautical Engineering (No.14) -AUSM Type Upwind Schemes-, Proceedings of 14th NAL Symposium on Aircraft Computational Aerodynamics, SP-34, pp. 7-12, 1997.
- 9) Taniichi, K. and Miyaji, K.: Development of Efficient Time-Spectral Method for Periodically Unsteady Flow Solutions, *J. of Jpn. Soc. Aeronaut. Space Sci.*, **65**, 2 (2017), pp. 73-81 (in Japanese).
- 10) Butsuen, J., Hirotsu, T., Taguchi, H., Hongoh, M., Hiruma, M., and Tezuka, A.: Lateral and Directional Aerodynamic Characteristics Evaluation of High-Mach Integrated Control Experimental Vehicle, Proceedings of 55th Aircraft Symposium, Matsue, Japan, JSASS-2017-5213, 2017 (in Japanese).
- 11) Hashimoto, A., Murakami, K., Aoyama, T., and Lahur, P.: Lift and Drag Prediction Using Automatic Hexahedra Grid Generation Method, AIAA Paper 2009-1365, 2009.
- 12) Hashimoto, A., Murakami, K., Aoyama, T., Ishiko, K., Hishida, M., Sakashita, M., and Lahur, P.: Toward the Fastest Unstructured CFD Code 'FaSTAR,' AIAA Paper 2012-1075, 2012.
- 13) Miyaji, K. and Yoshida, Y.: Prediction of Aircraft Dynamic Stability Derivatives Using Time-Spectral Computational Fluid Dynamics, *Trans. Jpn. Soc. Aeronaut. Space Sci.*, **62**, 6 (2019), pp.

291-297.

14) Miwa, H. and Ueno, M.: Development of Dynamic Stability

Equipment for Transonic Wind Tunnel, JAXA-RR-03-021, (2004), pp. 219-225 (in Japanese).

(a) Altitude vs. time

(b) Dynamic pressure vs. time

(c) Mach number vs. time

(d) Pitch angle vs. time

(e) α vs. time

(f) Altitude vs. down range

Fig. 12. Flight trajectories of nominal initial conditions.

(a) Altitude vs. time

(b) Dynamic pressure vs. time

(c) β vs. time

(d) Roll angle vs. time

(e) Yaw angle vs. time

(f) Cross-range vs. down range

Fig. 13. Flight trajectories with initial misalignment of roll/yaw-angle.