Oral presentation | Incompressible/compressible/hypersonic flow
Incompressible/compressible/hypersonic flow-III
Thu. Jul 18, 2024 10:45 AM - 12:45 PM Room D

[10-D-04] Effect of Chemical Reaction on the Flight Stability of the Hypersonic Vehicle at High Altitude

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Keywords: Hypersonic flow, Chemical reacting flow, Dynamic stability

Effect of Chemical Reaction on the Flight Stability of the Hypersonic Vehicle at High Altitude

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CONTENTS

Introduction

Demand for new flight platforms

- Capable of performing complex long-term missions at high altitudes or in space.
- Hypersonic glide vehicle and reusable space vehicles are developed recently.


[X-37b]


[Dream Chaser]

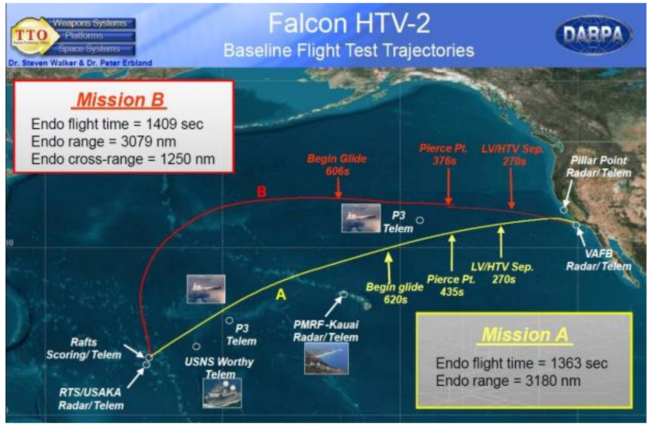

[IXV (Intermediate eXperimental Vehicle)]

Introduction

● Flight stability of space vehicles

- **Hypersonic vehicles are prone to flight instabilities.**
  - Smaller wings and control surfaces than conventional aircraft to withstand extreme flight conditions
  - Due to high altitude flight, dynamic pressure is insufficient to generate enough control force.
- **The failure of the first flight test of Falcon HTV–2 was caused by dynamic coupling between roll and yaw instabilities.**

[HTV–2]

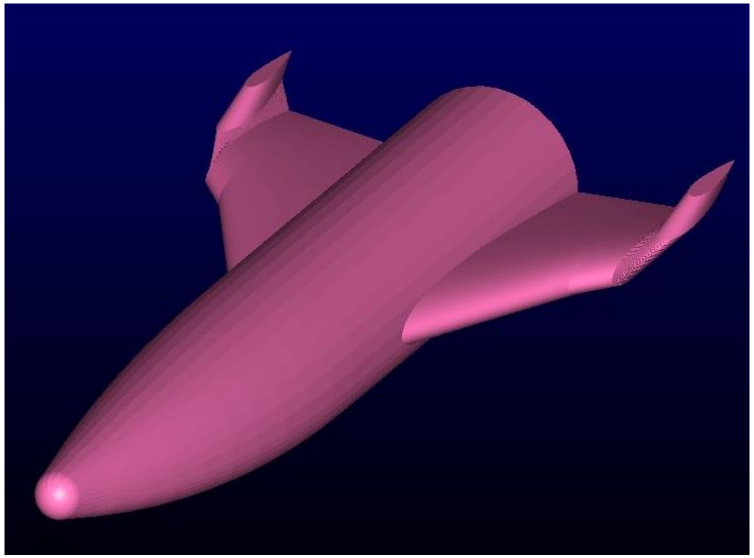


[Trajectory of Baseline Flight Test of HTV–2]

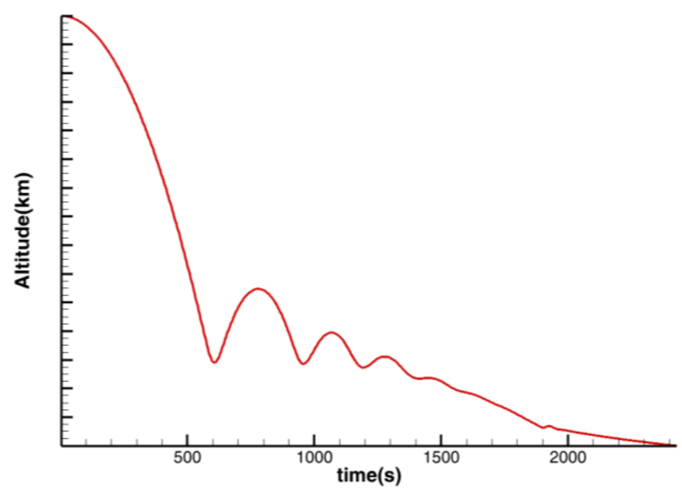
Introduction

● Research objective

- Examine the static and dynamic stabilities in the longitudinal direction of a preliminary designed hypersonic vehicle during its reentry flight (h ≤ 100 km).
- Examine the stability characteristics and find out under which condition the instabilities occur.
- → Identify the causes of instabilities and propose, if possible, remedies in the future.



[Geometry of Reusable Space Vehicle]



[Nominal Trajectory of Reusable Space Vehicle]

Computational Framework

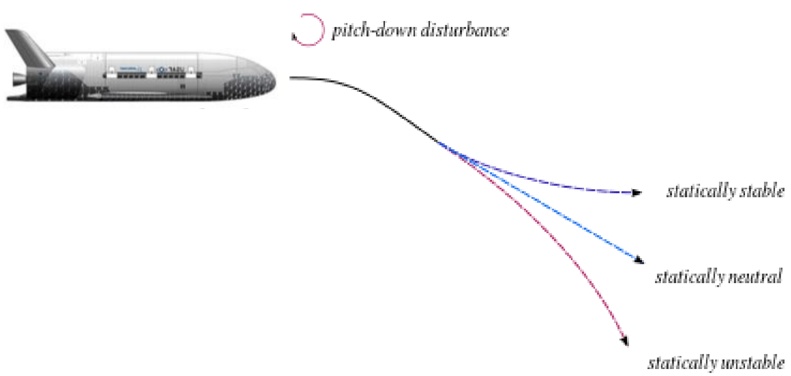
● Longitudinal flight stability

▪ Static stability

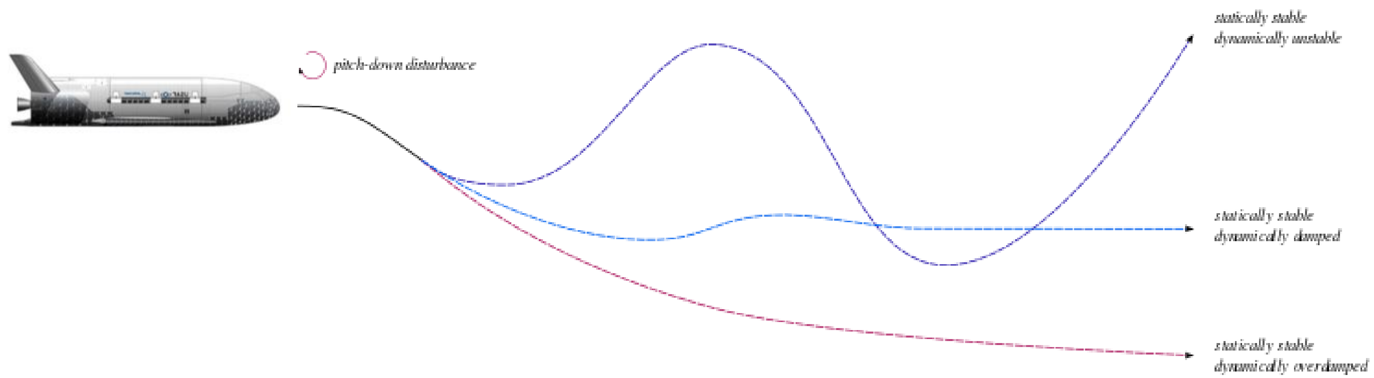
- Initial tendency on pitching
  - ✓ When a pitch–down disturbance occurs on a statically stable aircraft, a nose–up pitch moment acts on the aircraft, and it will recover its original attitude.

▪ Dynamic stability

- Whether oscillations tend to increase, decrease or stay constant.
  - ✓ When a pitch–down disturbance occurs on a dynamically unstable aircraft, the oscillation due to the disturbance amplifies over time and the aircraft may fall.



[Schematic Diagram of Static Stability]



[Schematic Diagram of Dynamic Stability]

Computational Framework

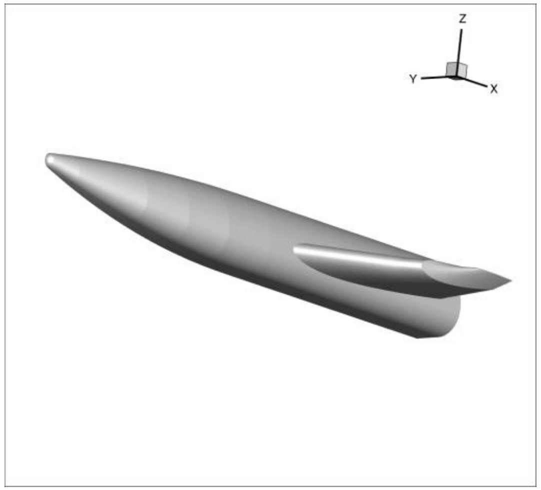
Examine longitudinal stability derivatives

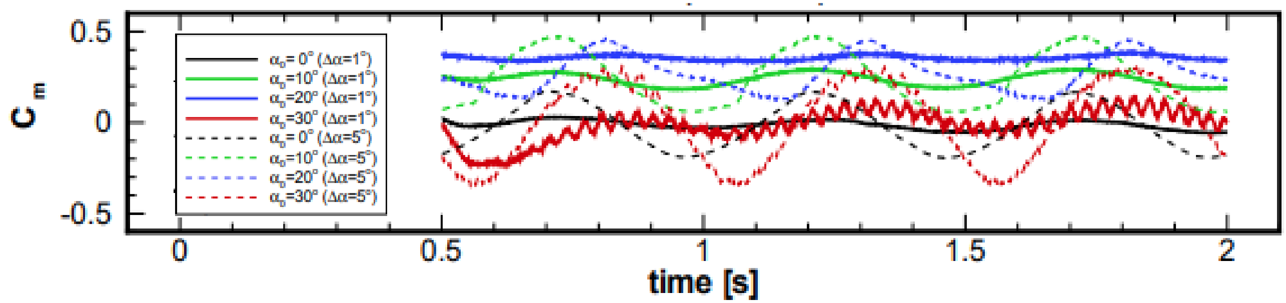
- **Free oscillation, Frequency domain vs. Forced oscillation**
- **Forced oscillation technique**
  - Measure the forces and moments while oscillating the vehicle w.r.t. its center of gravity.

$$\alpha(t) = \alpha_0 + \alpha_A \sin\omega t \qquad q = \dot{\alpha}(t) = \alpha_A \omega \cos\omega t$$

  - The response of the forces and moments to the motion of the vehicle is also sinusoidal, with some phase difference.

$$C_M(t) = C_{M_0} + C_{M_A}\sin(\omega t - \delta) = C_{M_0} + C_{M_A}\sin\omega t\cos\delta - C_{M_A}\cos\omega t\sin\delta$$





[Example of the Response of the Pitching Moment to the Sinusoidal Motion]

Computational Framework

Examine longitudinal flight stability derivatives

Forced oscillation technique (cont'd)

- The pitching moment also can be expanded using Taylor series

$$C_M(t) = C_{M_0} + C_{M_\alpha}(\alpha(t) - \alpha_0) + C_{M_{\dot\alpha}} \frac{\dot\alpha(t)\,\bar c}{2V} + C_{M_q} \frac{q\bar c}{2V} + \cdots$$

- Substitute the angle of attack. the angular velocity, and pitch rate

$$\alpha(t) = \alpha_0 + \alpha_A \sin\omega t \qquad q = \dot\alpha(t) = \alpha_A \omega \cos\omega t$$

$$C_M(t) = C_{M_0} + C_{M_\alpha}\alpha_A \sin\omega t + \left(C_{M_{\dot\alpha}} + C_{M_q}\right) k\alpha_A \cos\omega t$$

- Combine with the equations of pitching moment in the previous slide

$$C_{M_\alpha} = \frac{C_{M_A}\cos\delta}{\alpha_A}, \quad C_{M_{\dot\alpha}} + C_{M_q} = -\frac{C_{M_A}\sin\delta}{k\alpha_A}$$

Computational Framework

Examine longitudinal flight stability derivatives

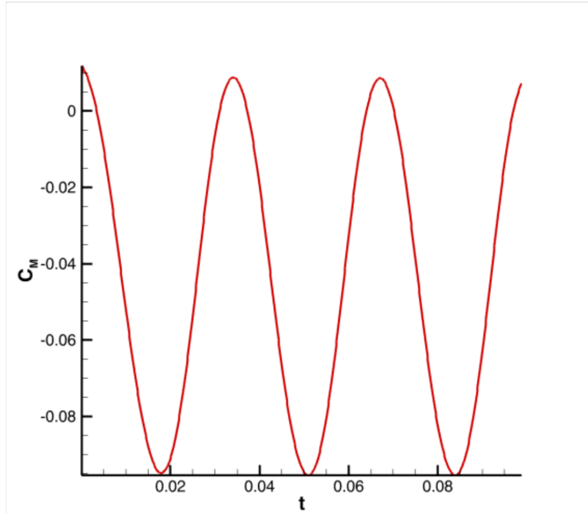
Forced oscillation technique (cont'd)

- The pitching moment can be fitted to sine and cosine functions at every time step.
- Solve the over–determined system of equations using the least squares method to minimize error

$$C_M\left(t_i\right) = A_0 + A_1 \sin \omega t_i + A_2 \cos \omega t_i + e_i$$

$$\begin{bmatrix} C_m\left(t_1\right) \\ C_m\left(t_2\right) \\ \vdots \\ C_m\left(t_n\right) \end{bmatrix} = \begin{bmatrix} 1 & \sin \omega t_1 & \cos \omega t_1 \\ 1 & \sin \omega t_2 & \cos \omega t_2 \\ \vdots & \vdots & \vdots \\ 1 & \sin \omega t_n & \cos \omega t_n \end{bmatrix} \begin{bmatrix} A_0 \\ A_1 \\ A_2 \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{bmatrix}$$

$$\rightarrow A_0 = C_{M_0},\ A_1 = C_{M_A} \cos \delta,\ A_2 = -C_{M_A} \sin \delta$$



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2.7000000000000000e+01	3.1777920000000046e-03	1.1618469474548268 1e-01

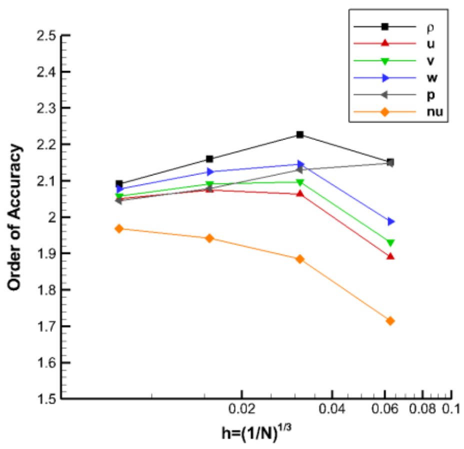
[Pitching Moment Graph and Data]

Computational Framework

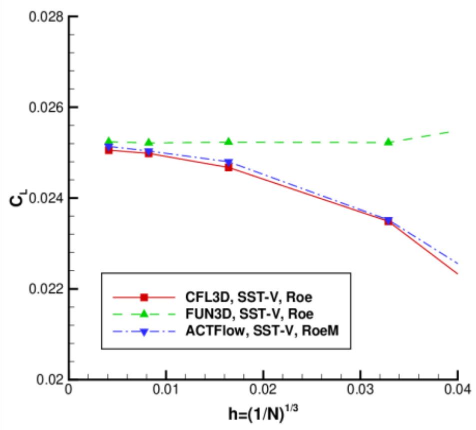
● ACTFlow[1]

[1] C. Lee, et. al., *AIAA SciTech Forum*, 2021

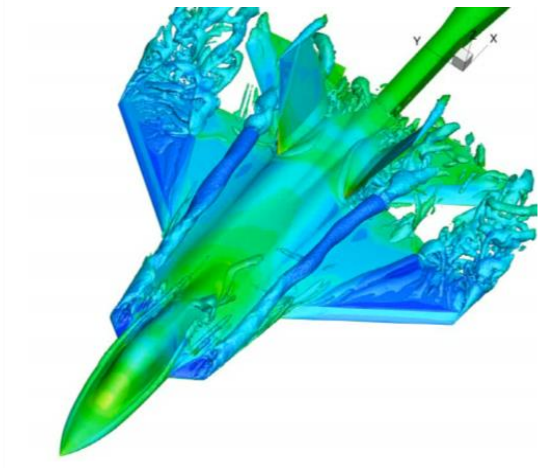
- A 2nd-order finite volume in-house solver based on unstructured mixed grids
- Compressible RANS equations with low-Mach number preconditioning
- Extensively verified and validated using MMS and NASA TMR website
- Suitable for simulating complex 3-D flows (fighter, engine nozzle etc.)



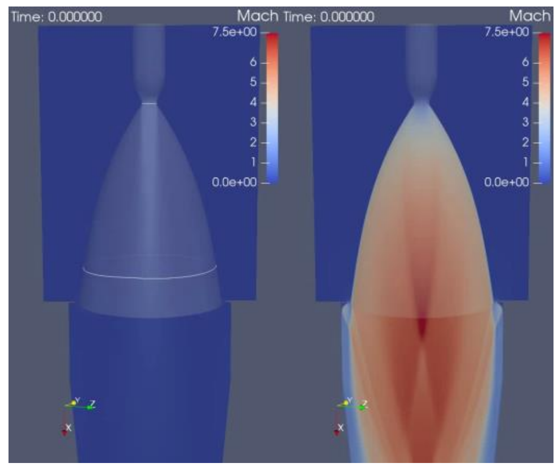
[MMS Results for SA-noft2]



[Force Convergence of 3-D Bump]



[Flow Simulation on a Fighter (Q-criterion iso-surface)]

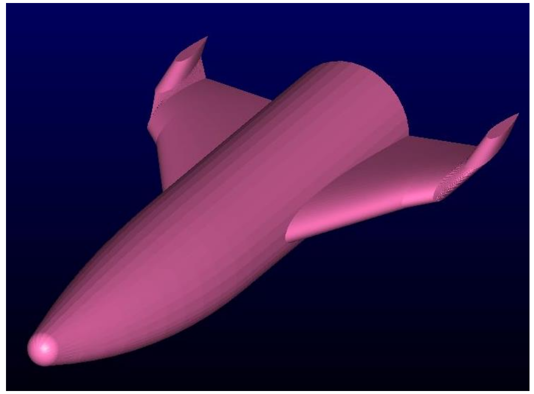


[Left: Engine Startup, right: Engine Shutdown]

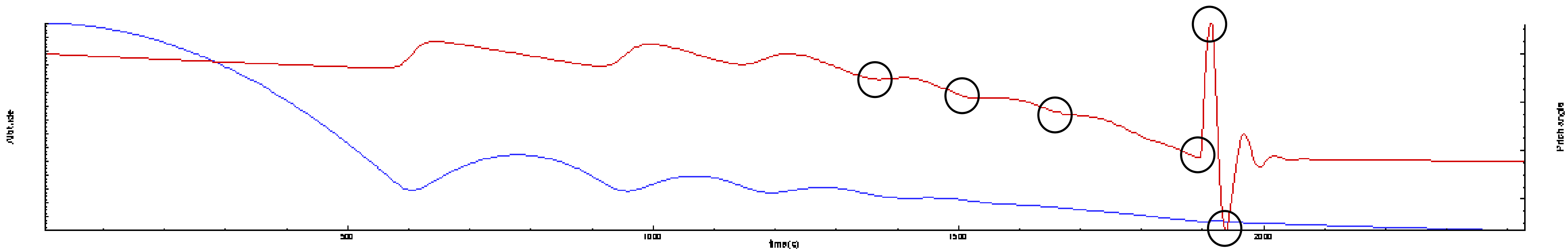
Numerical Results

● Longitudinal stability of a reusable space vehicle

- **Target geometry: a preliminary designed space vehicle**
  - 2 wings, no vertical and horizontal tails
  - Assume that no control surfaces are deflected
- **Eight conditions have been selected for investigation along the designed trajectory**
  - Vehicle descends gradually as it bounces up and down.
    - ✓ In order to maintain the angles of attack, the vehicle pitches up and down.
  - After 1,900 seconds, vehicle pitches up and down rapidly for 100 seconds (phugoid mode).



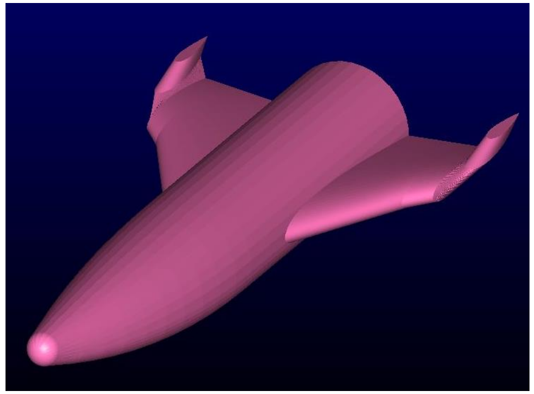
[Target Geometry]



[Nominal Trajectory of the Target Geometry]

Numerical Results

- **Longitudinal stability of a reusable space vehicle**
  - **Target geometry: a preliminary designed space vehicle**
    - 2 wings, no vertical and horizontal tails
    - Assume that no control surfaces are deflected
  - **Eight conditions have been selected for investigation along the designed trajectory**
    - Conditions suspected of instability



[Target Geometry]

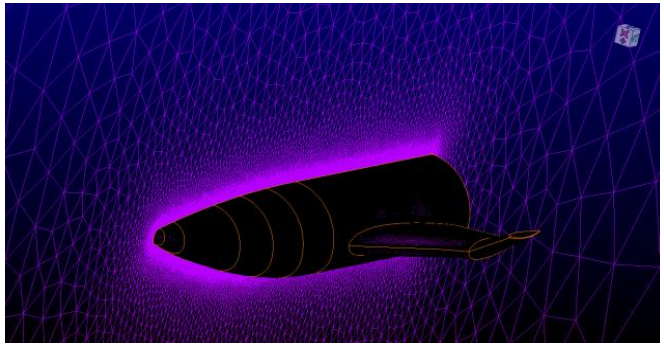
[Flight Conditions]

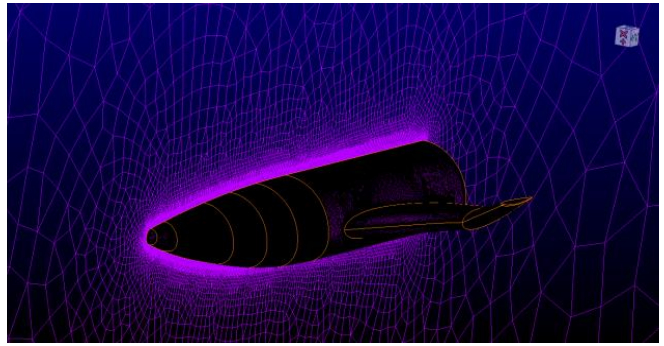
	Mach	Altitude (km)	AOA (°)	Reynolds #
case 1	0.3	6.7	12.5	33.8×10^6
case 2	0.43	12.9	13.1	22.5×10^6
case 3	0.45	13.1	13.3	24.5×10^6
case 4	0.96	12.4	15.2	54.3×10^6
case 5	1.5	20.3	17	24.7×10^6
case 6	3.0	32.0	20.4	7.8×10^6
case 7	5.0	41.2	25.3	3.1×10^6
case 8	8.0	51.1	33.3	1.3×10^6

Numerical Results

● Longitudinal stability of a reusable space vehicle

- **Computational grids**
  - Subsonic ~ transonic: 12.5 M / half-body / y+ = 1
  - Supersonic ~ hypersonic: 18.2 M / half-body / y+ = 1
- **Numerical components of ACTFlow**
  - Flux scheme: AUSMPW+
  - Limiter: MLP-u2
  - Time integration: Implicit BDF2 with dual time stepping
  - Linear solver: GMRES
  - Turbulence model: Menter's k-ω SST
  - EOS: Ideal gas law





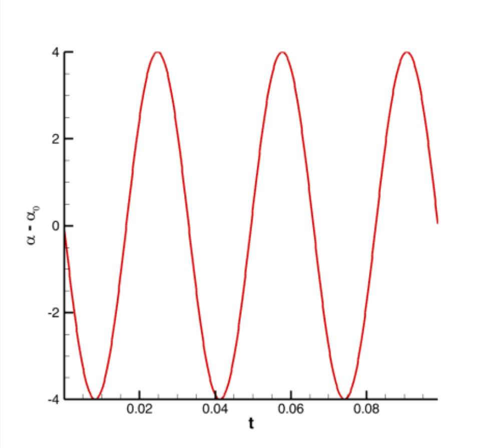
[Computational Grids (up: subsonic, bottom: supersonic)]

Numerical Results

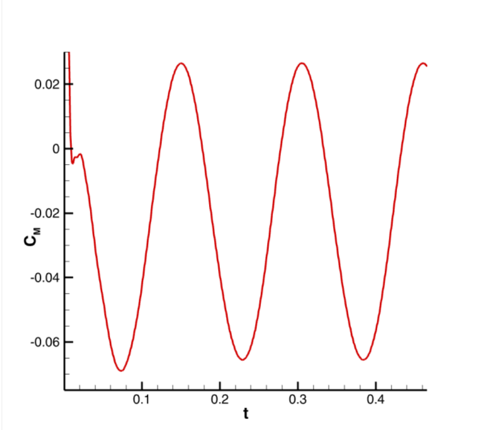
● Longitudinal stability of a reusable space vehicle

▪ Forced oscillation conditions

- Subsonic ~ transonic
  - ✓ Average AOA (α_0): 12.5°/13.1°/13.3°/15.2°/17°
  - ✓ Amplitude (α_A): 4°
  - ✓ Reduced frequency ($\omega = (f \cdot \bar{c})/2V$): 2.0
  - ✓ Center of rotation: 60.8% of model size from nose (C.G. point)
    - ➢ Assume uniform mass distribution
  - ✓ Target time: 0.099 s ~ 0.466 s (3 periods)
- Supersonic ~ hypersonic
  - ✓ Average AOA (α_0): 20.4°/25.2°/33.3°
  - ✓ Amplitude (α_A): 2°, 4°
  - ✓ Reduced frequency ($\omega = (f \cdot \bar{c})/2V$): 1.0
  - ✓ Target time: 0.04817 s ~ 0.05577 s (3 periods)



[Change of Angle of Attack over Time]



[Pitching Moment of the Vehicle]

Numerical Results

● Longitudinal stability of a reusable space vehicle

- Subsonic cases

[Flight Conditions]

	Mach	Altitude (km)	AOA (°)	Reynolds #
case 1	0.3	6.7	12.5	33.8×10^6
case 2	0.43	12.9	13.1	22.5×10^6
case 3	0.45	13.1	13.3	24.5×10^6
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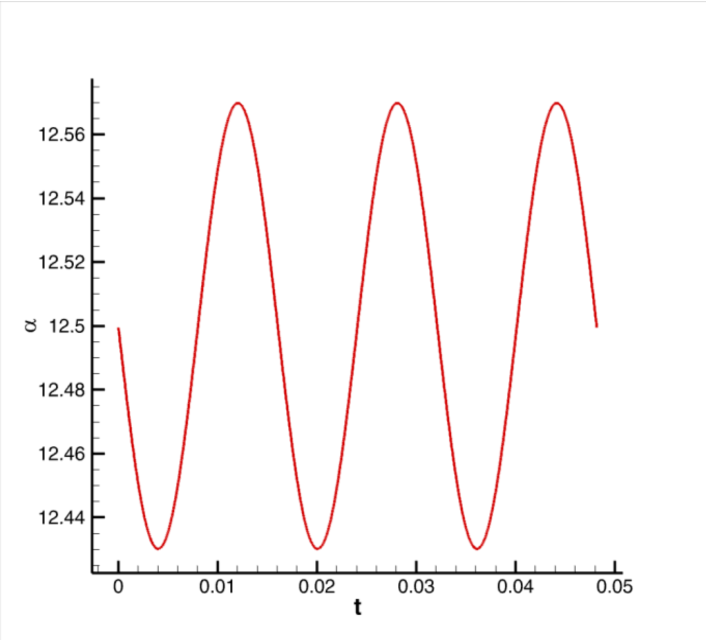
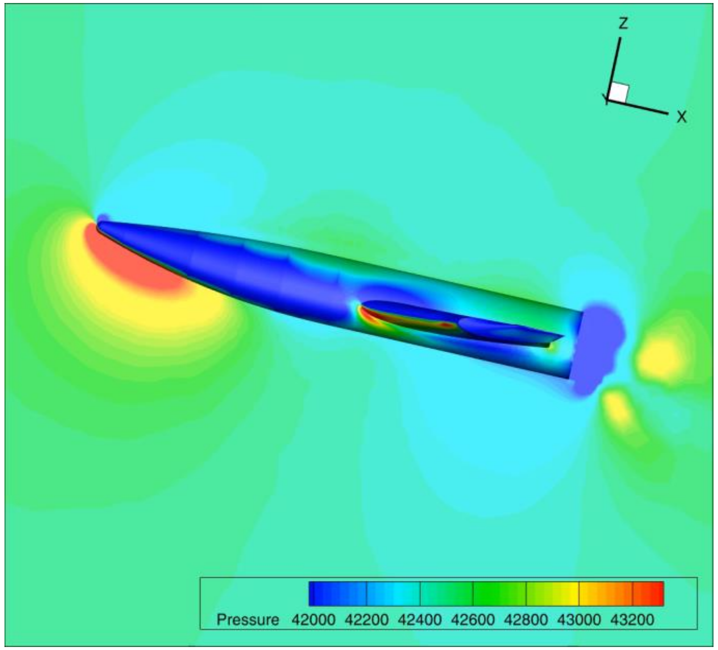
Numerical Results

● Longitudinal stability of a reusable space vehicle

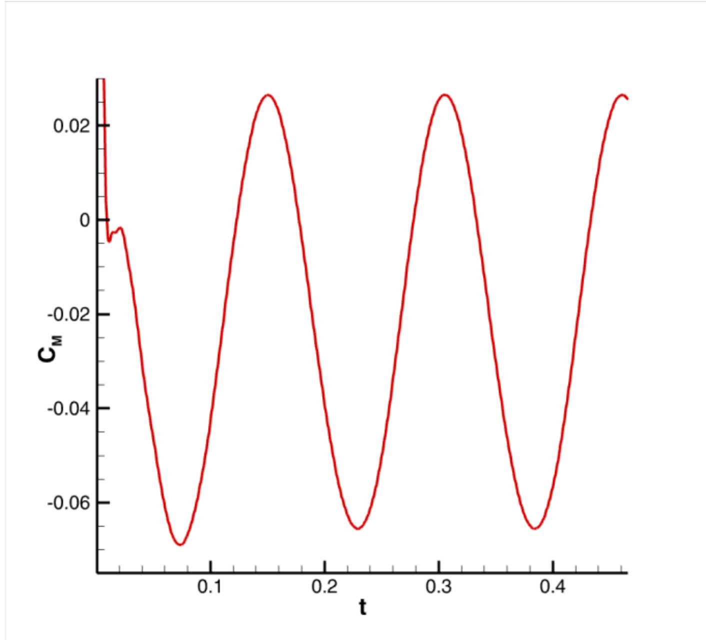
- Subsonic cases



[Change of Angle of Attack over Time]



[Video of the Vehicle]



[Pitching Moment of the Vehicle]

Numerical Results

Longitudinal stability of a reusable space vehicle

Subsonic cases

- All three cases show that the vehicle has negative C_M, C_{M_α}, and $C_{M_{\dot{\alpha}}} + C_{M_q}$.
- → The vehicle is statically and dynamically stable at these conditions.

✓ The results of the three cases are similar because of similar freestream conditions.

[Stability Coefficients]

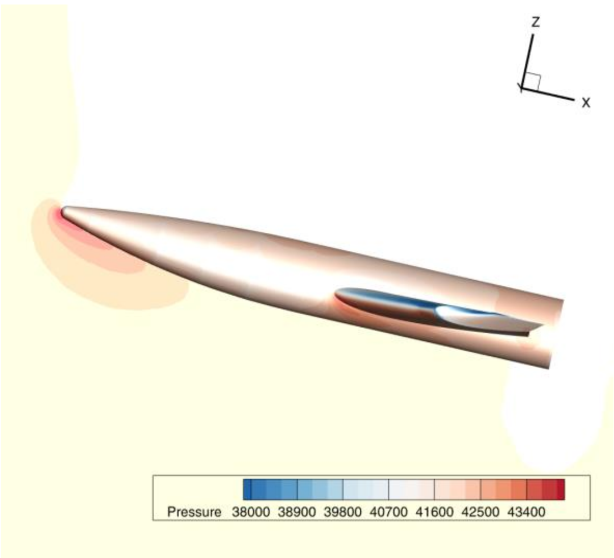
	Mach	C_M	C_{M_α}	$C_{M_{\dot{\alpha}}} + C_{M_q}$
case 1	0.3	−0.3049	−0.1276	−0.3235
case 2	0.43	−0.4871	−0.1370	−0.3462
case 3	0.45	−0.3049	−0.1417	−0.3504

Numerical Results

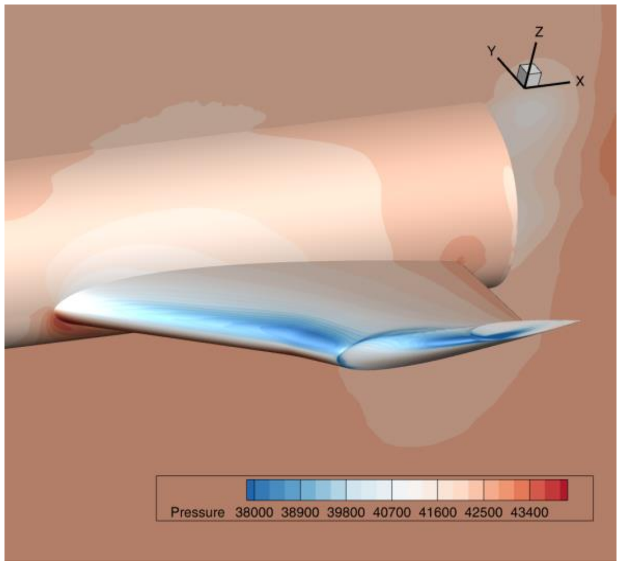
● Longitudinal stability of a reusable space vehicle

▪ Subsonic cases

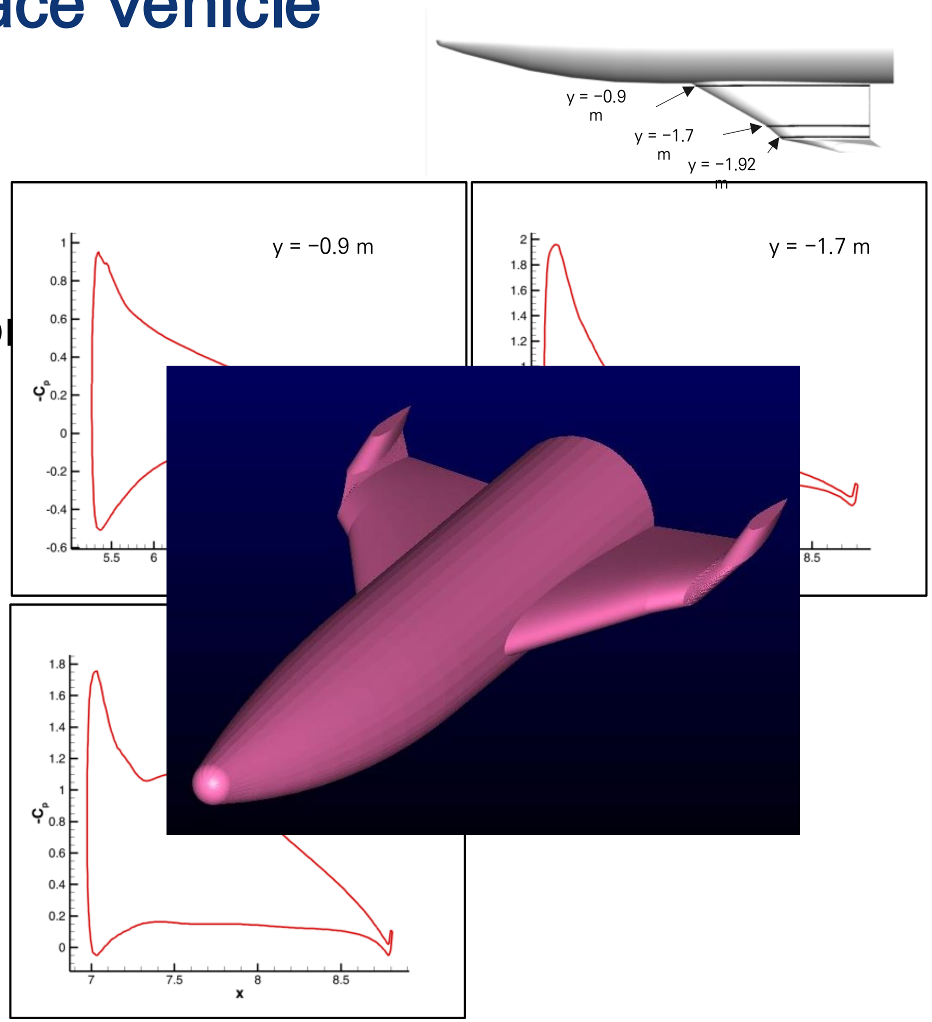
- Leading edge vortex is generated as is typical in delta wings.
- No shockwaves or massive flow separatio



[Pressure around the Vehicle]



[Pressure around the Wing]



Numerical Results

● Longitudinal stability of a reusable space vehicle

- Supersonic and hypersonic cases

[Flight Conditions]

	Mach	Altitude (km)	AOA (°)	Reynolds #
case 1	0.3	6.7	12.5	33.8×10^6
case 2	0.43	12.9	13.1	22.5×10^6
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case 4	0.96	12.4	15.2	54.3×10^6
case 5	1.5	20.3	17	24.7×10^6
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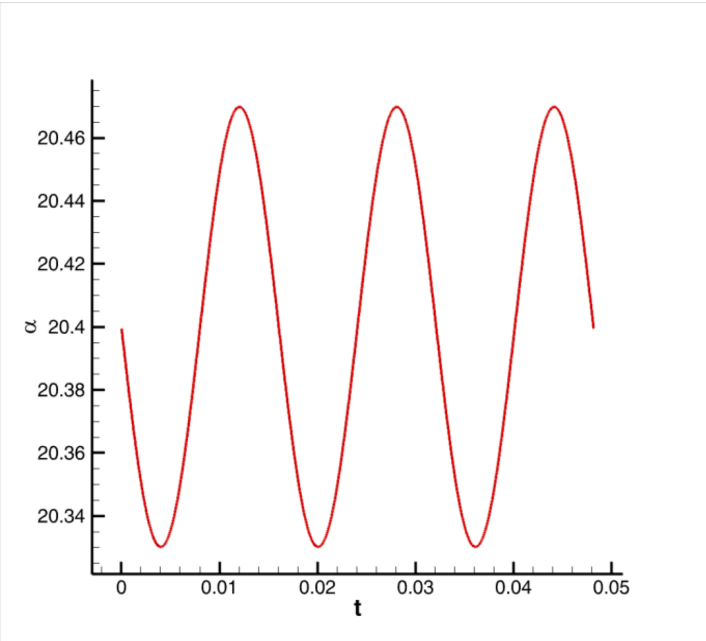
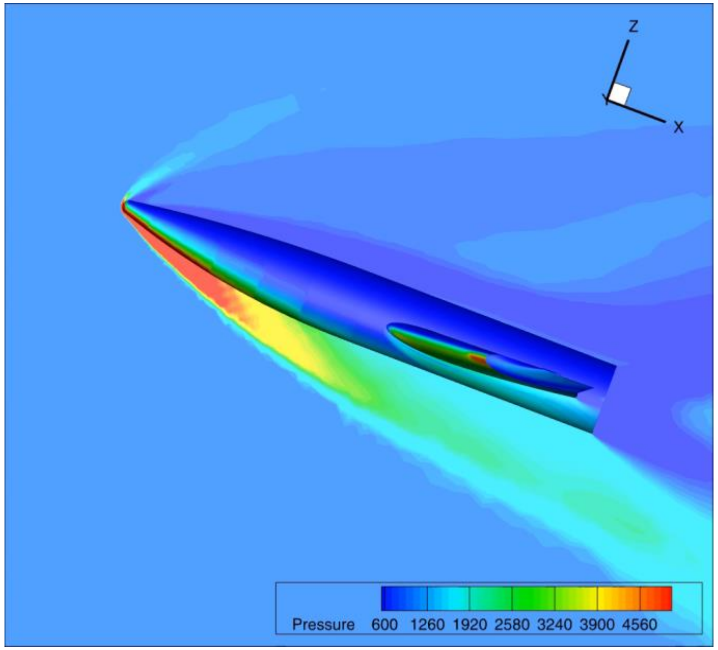
case 7	5.0	41.2	25.3	3.1×10^6
case 8	8.0	51.1	33.3	1.3×10^6

Numerical Results

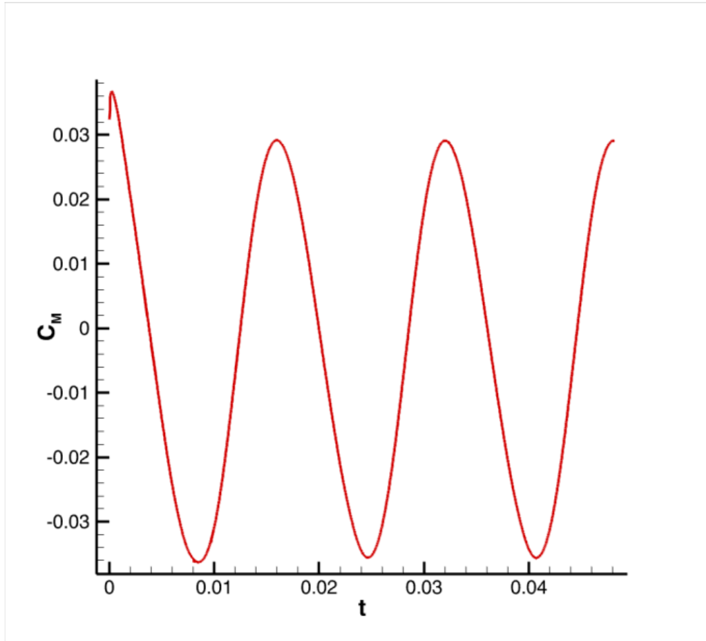
- Longitudinal stability of a reusable space vehicle
  - Supersonic and hypersonic cases



[Change of Angle of Attack over Time]



[Video of the Vehicle]



[Pitching Moment of the Vehicle]

Longitudinal stability of a reusable space vehicle

Supersonic and hypersonic cases

- All four cases show that the vehicle has negative C_M, C_{M_α}, and $C_{M_{\dot{\alpha}}} + C_{M_q}$.
- → The vehicle is statically and dynamically stable at these conditions.

[Stability Coefficients]

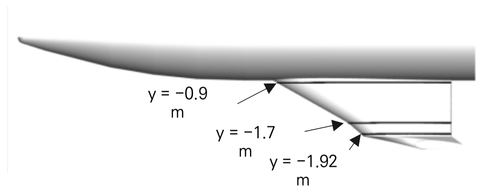
	Mach	C_M	C_{M_α}	$C_{M_{\dot{\alpha}}} + C_{M_q}$
case 5	1.5	−0.4488	−0.1876	−0.3619
case 6	3.0	−0.3151	−0.0387	−0.2782
case 7	5.0	−0.3335	−0.1314	−0.2782
case 8	8.0	−0.4755	−0.0030	−0.4238

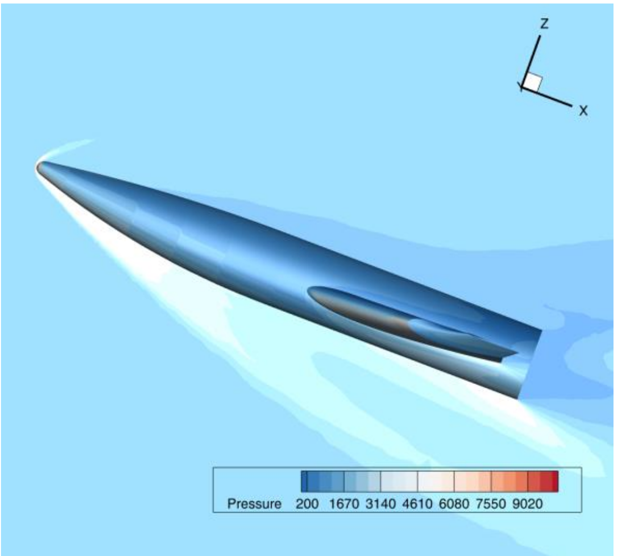
Numerical Results

Longitudinal stability of a reusable space vehicle

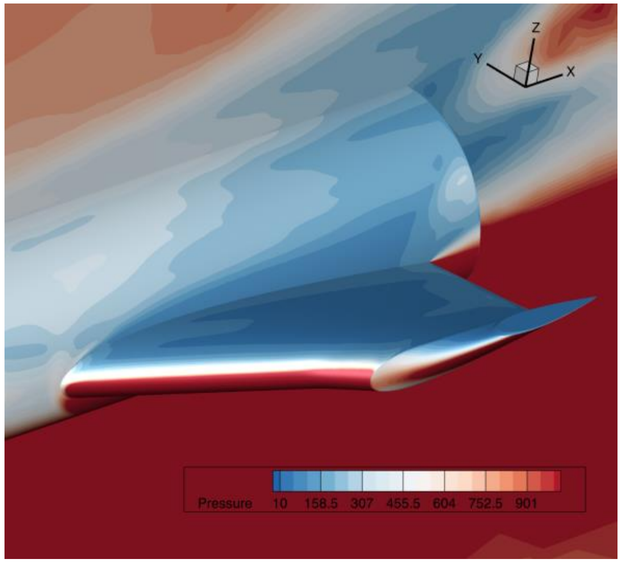
▪ Supersonic and hypersonic cases

- The shock stands in front of the nose of the vehicle.
- Flow separation from the upper surface of the wing, covering the entire region of the wing.

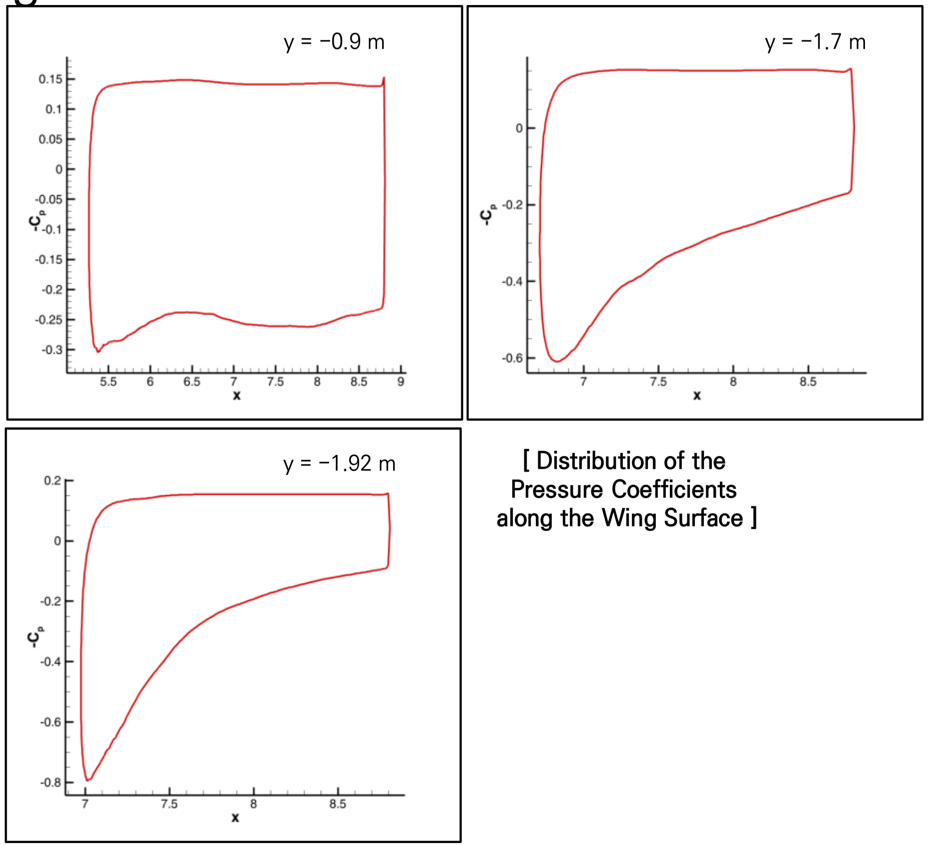




[Pressure around the Vehicle]



[Pressure around the Wing]



[Distribution of the Pressure Coefficients along the Wing Surface]

Numerical Results

● Longitudinal stability of a reusable space vehicle

- Transonic case

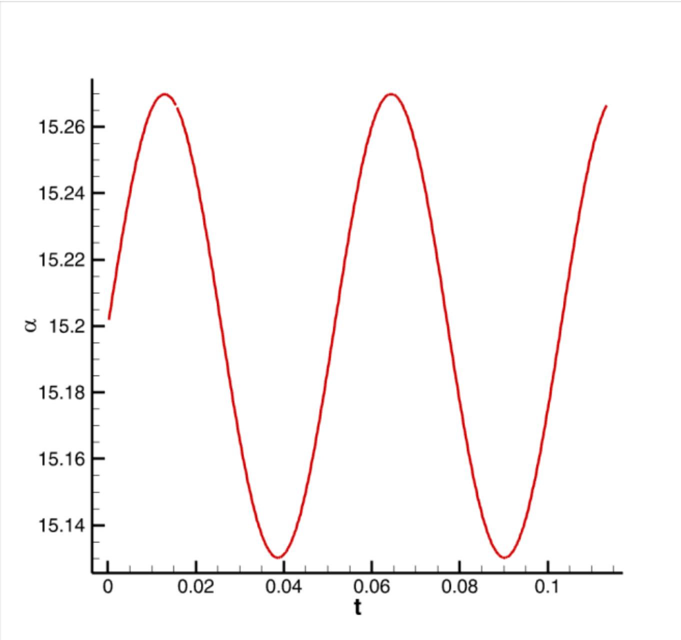
[Flight Conditions]

	Mach	Altitude (km)	AOA (°)	Reynolds #
case 1	0.3	6.7	12.5	33.8×10^6
case 2	0.43	12.9	13.1	22.5×10^6
case 3	0.45	13.1	13.3	24.5×10^6
case 4	0.96	12.4	15.2	54.3×10^6
case 5	1.5	20.3	17	24.7×10^6
case 6	3.0	32.0	20.4	7.8×10^6
case 7	5.0	41.2	25.3	3.1×10^6
case 8	8.0	51.1	33.3	1.3×10^6

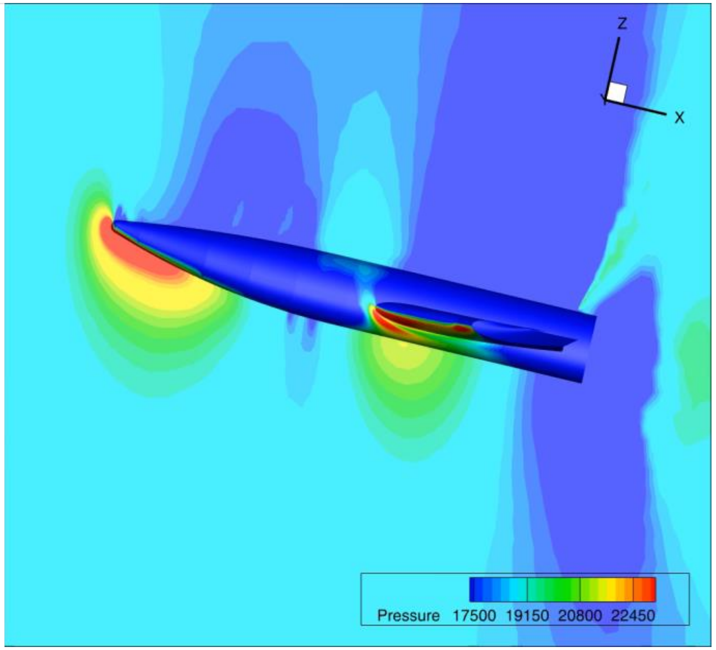
Numerical Results

● Longitudinal stability of a reusable space vehicle

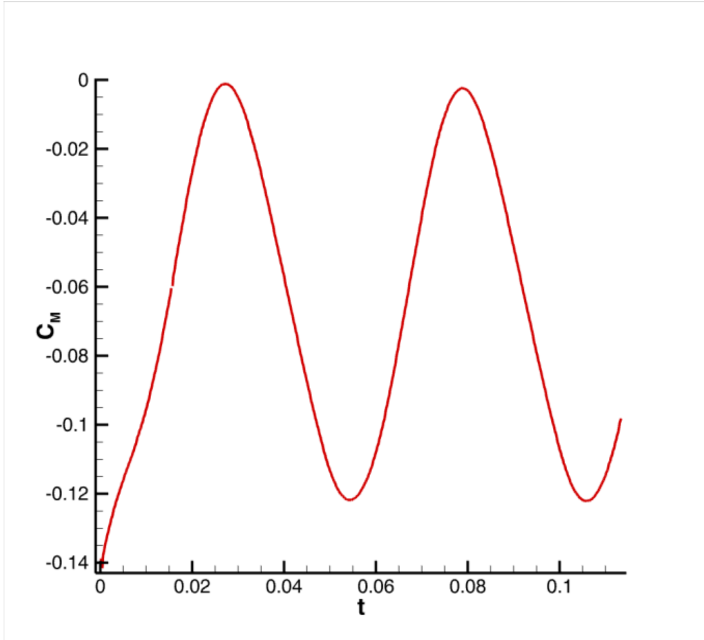
- Transonic case



[Change of Angle of Attack over Time]



[Video of the Vehicle]



[Pitching Moment of the Vehicle]

Numerical Results

Longitudinal stability of a reusable space vehicle

Transonic case

- Transonic case shows that the vehicle has negative C_M, C_{M_α}, positive $C_{M_{\dot{\alpha}}} + C_{M_q}$.
- At this condition, the vehicle is statically stable but dynamically unstable.
- → Oscillation caused by disturbance diverges slowly.

[Stability Coefficients]

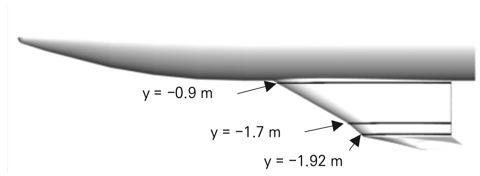
	Mach	C_M	C_{M_α}	$C_{M_{\dot{\alpha}}} + C_{M_q}$
case 4	0.96	−0.4874	−0.2315	0.4053

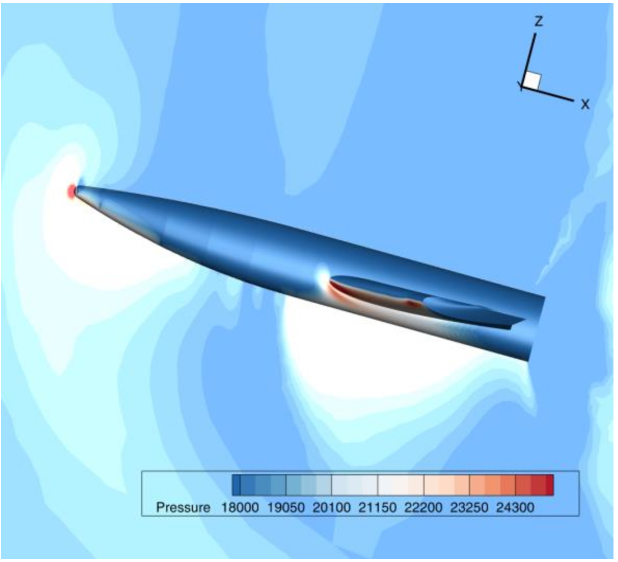
Numerical Results

● Longitudinal stability of a reusable space vehicle

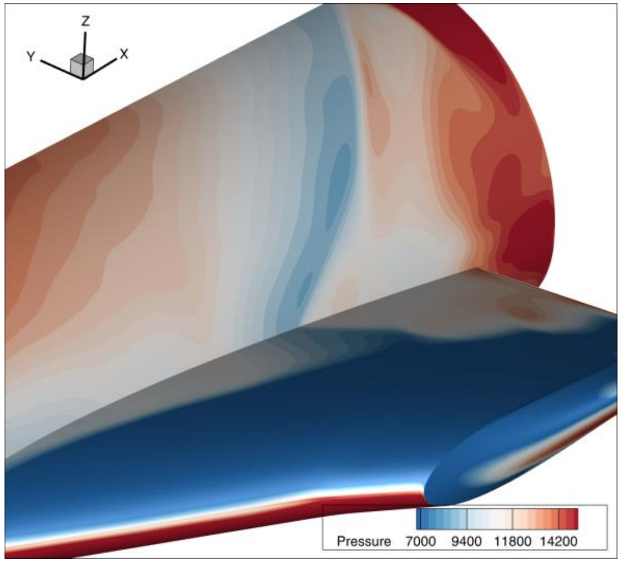
▪ Transonic cases

- The leading edge vortex expands toward the root.
- There is a shock at the upper wing–fuselage junction.
- Interaction between junction shock and LEV plays an important role in instability.

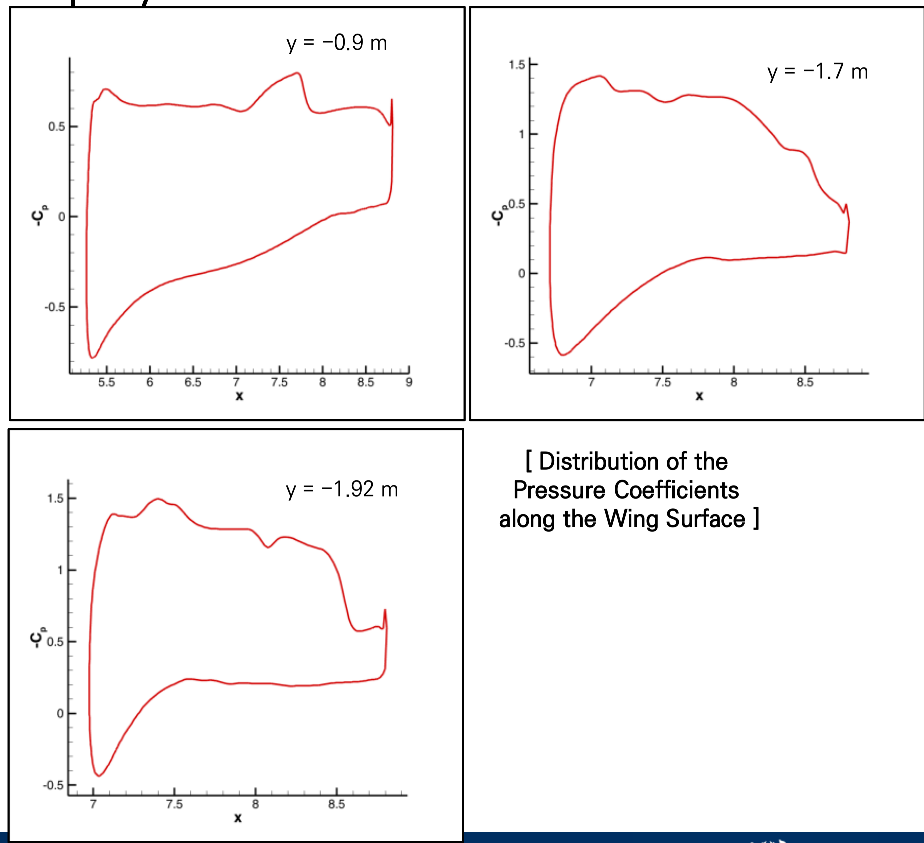




[Pressure around the Vehicle]



[Pressure around the Wing]



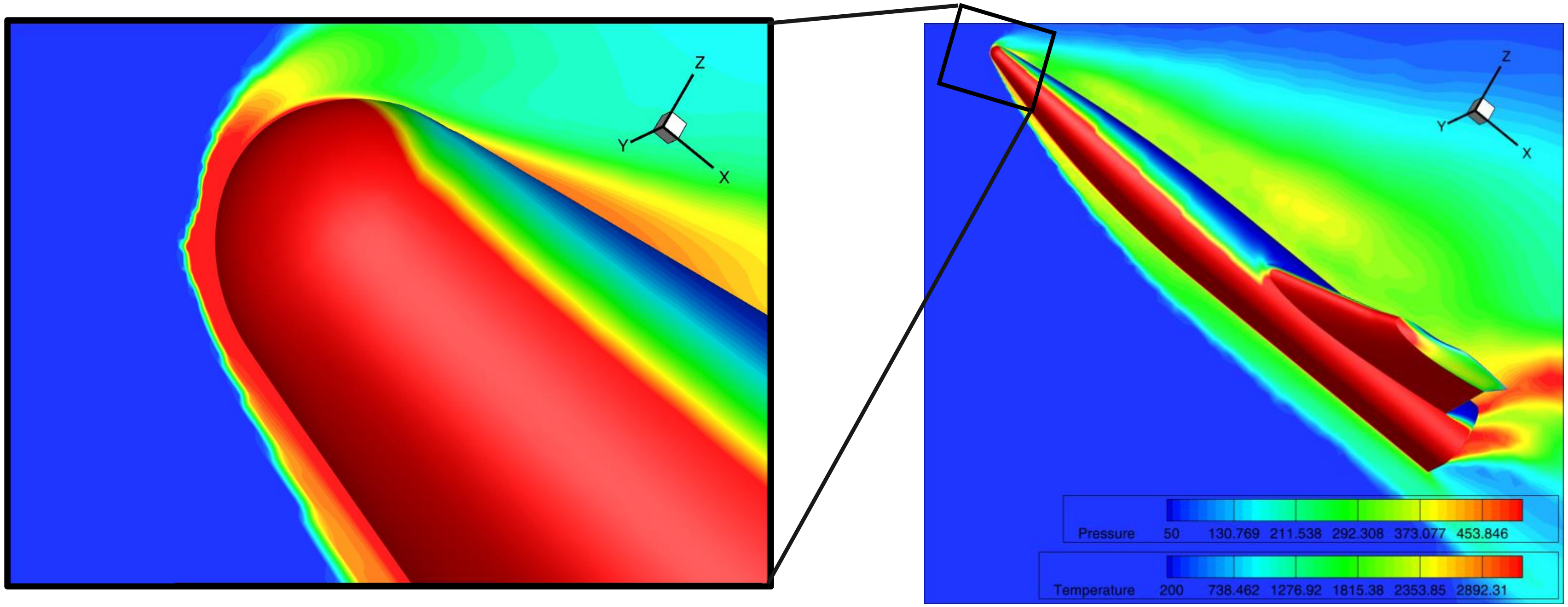
[Distribution of the Pressure Coefficients along the Wing Surface]

Numerical Results

● Longitudinal stability of a reusable space vehicle

▪ Effects of chemical reaction at case 8

- The temperature around the nose in case 8 is over 3,000 K, which is high enough to induce dissociation of oxygen molecules.



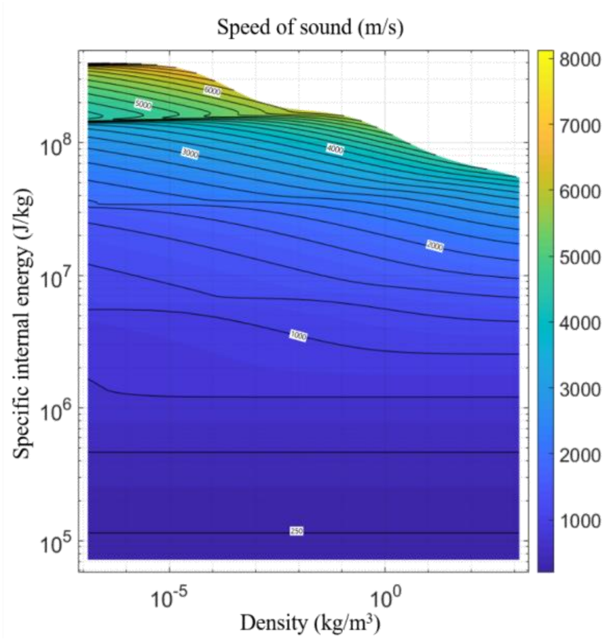
[Temperature around Vehicle]

Numerical Results

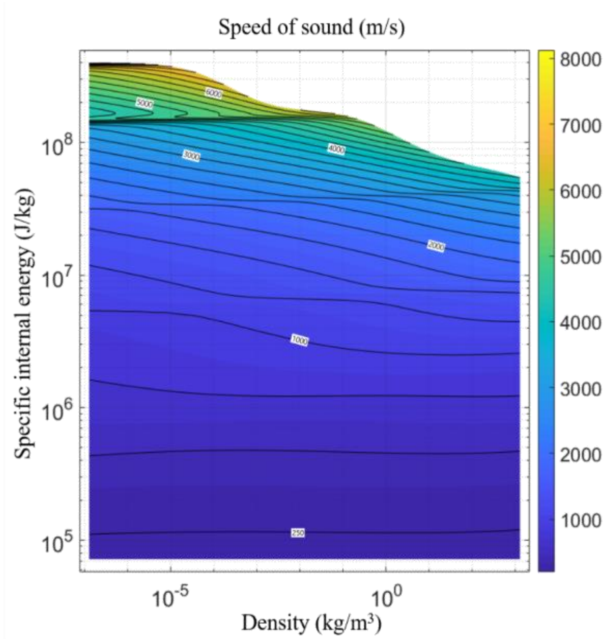
[1] H. You el. al., *Computer Physics Communications*, 2023

● IDEA (Infinitely Differentiable Equilibrium Air)[1]

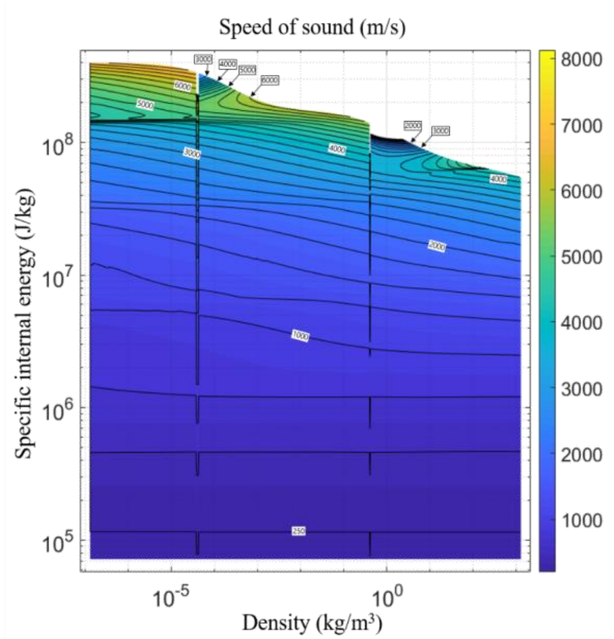
- **An open-source library to predict equilibrium air properties based on ANN**
- **Obtain training data based on kinetic molecular theory**
  - 11-species air (N2, O2, N, O, NO, NO+, N+, O+, N++, O++, e−)



[Training Data]



[25000 K, 5% model (N_p = 49)]



[Srinivasan's model (N_p = 375)]

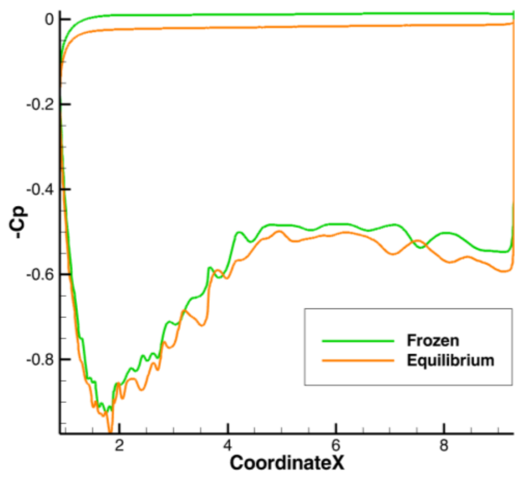
Numerical Results

● Longitudinal stability of a reusable space vehicle

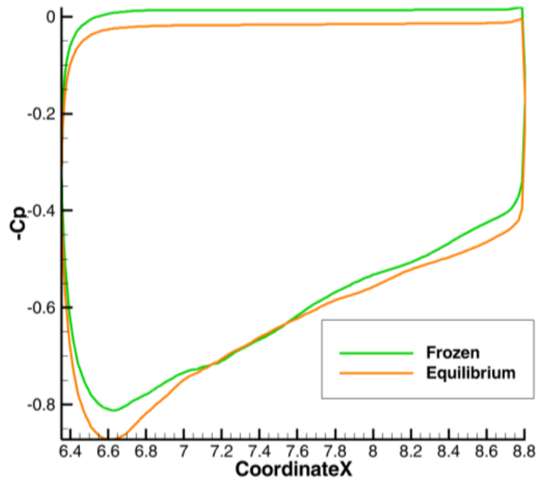
	C_M
Frozen	−0.4785
Equilibrium	−0.4755

▪ Effects of chemical reaction at case 8

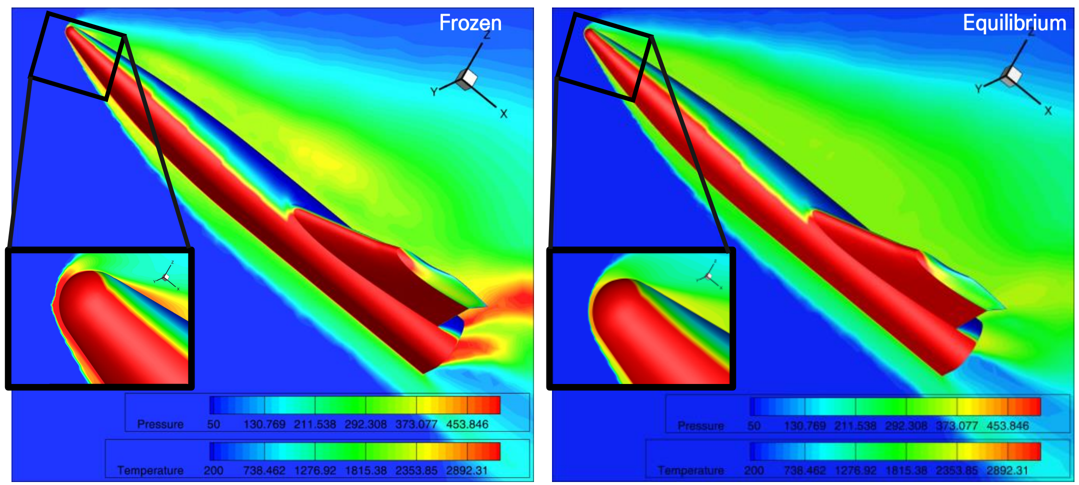
- Surface pressure of the two numerical results are almost identical.
- The maximum difference of surface pressure locates at x = 6.6 ($\Delta p \approx 100\ Pa$).
  - ✓ It is located near the c.g. point, and does not significantly affect to CM.
- Temperatures around the vehicle are similar except near the nose and base
  - ✓ At these regions, the excitation of vibrational energy and dissociation of oxygen molecule may occur.



[Cp along Surface of the Fuselage (y = −0.35)]



[Cp along Surface of the Wing (y = −1.5)]



[Temperature Distribution around the Vehicle and Surface Pressure]

Conclusions & Future works

Conclusions

- Longitudinal flight stability of a preliminary designed hypersonic vehicle has been investigated using forced oscillation technique.
  - Mach $\leq$ 8, altitude $\leq$ 50 km
- Under these conditions, the hypersonic vehicle remains stable except the transonic regime.
- At transonic condition, interaction between junction shock and leading edge vortex may cause instability.
- For Mach 8 case, the small difference between the frozen and equilibrium air results appears due to the temperature not high enough to induce chemical reactions.
  - Around the nose and base, the dissociation of oxygen molecules may occur.

Future works

- Examine the flight stability of the hypersonic vehicle at high-altitude ($\geq$ 60 km) and high-Mach number ($\geq$ 10)
  - Effects of the thermo-chemical models (frozen/equilibrium/non-equilibrium)