



Dynamic Stability Analysis of Air Taxis using Navier Stokes Equations

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Background

- **Electric Air taxis are becoming an alternative to helicopters**
 - **Energy efficient, Speed, Passenger friendly, Quieter, Less pollution**
- **Electric Vertical take-off and landing (eVTOL) configurations built with multiple pushing and lifting propellers are more popular**
 - **No need for runway, infrastructure in the cities, or adapt for vertiports**
- **eVTOL is more susceptible to instabilities from atmospheric turbulence and possible bird-strikes since**
 - **lighter and fly at lower altitude (1000 to 4000 ft) than conventional jet-fueled aircraft**
 - **instabilities such as Dutch Roll oscillations can occur**
- **Current stability analysis methods are limited to use of linear aerodynamics method which may not be adequate for air taxis**
- **This talk presents a procedures for stability analysis using time accurately coupled High-Fidelity Fluid and Structural equations on High Performance Computers**



Objective

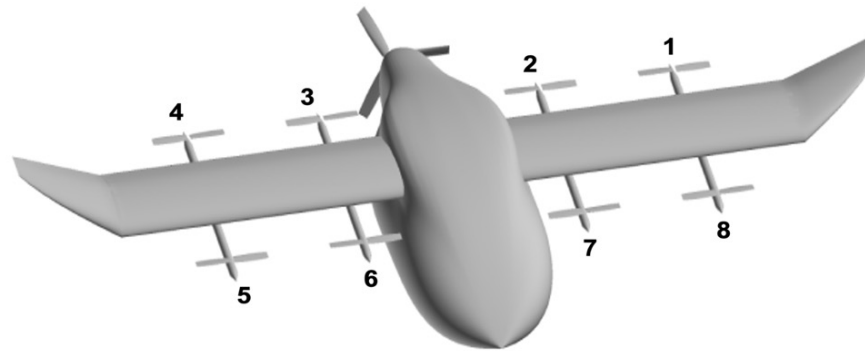
- **To present a summary of time domain procedures for stability analysis of eVTOL by using non-linear flow equations**
 - **Use Navier-Stokes equations with turbulence modelling**
 - **Use suitable stability and trajectory equations**
 - **Develop Supercomputer based frameworks**
 - **Address active oscillation suppression method**
 - **Demonstrate results for a typical eVTOL Air Taxi**
 - **Take-off simulation**
 - **Prediction of Dutch-Roll oscillations**
 - **Active Control of Lateral Instability**
 - **Effect of gust on flight**
 - **A framework to simulate landing with parachutes**



Typical eVTOL Configuration



eVTOL with Tail for Controls



eVTOL without Tail for Active Controls



Solver Approaches

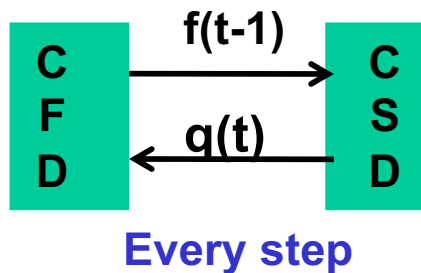
- **Flow equations**
 - **Unsteady Reynolds averaged Navier-Stokes (URANS) equations**
 - **Spalart-Allmaras turbulence models**
 - **Diagonal form of Beam-Warming central difference solver**
 - **Body fitted Structured overset grid**
 - **Implemented in OVERFLOW**
- **Lagrange's structural equations of motion**
 - **Finite element and modal form**
 - **2-DOF – Take-off Equations**
 - **Dutch-Roll Equations**
- **Time Integration**
 - **Numerically efficient Newmark's Explicit Method**
 - **Since the time step needed is dictated by fluids solver which is an order of magnitude smaller than that required for structural solver, explicit time integration is found accurate and numerically efficient**



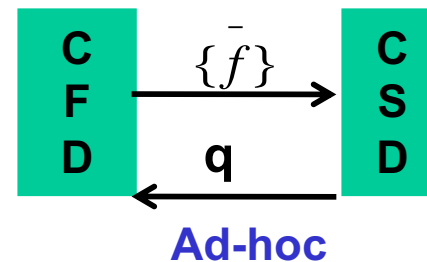
Coupled Procedures Using CFD/CSD

- Can be grouped into two categories based on type of fluid/structure coupling

**TA-time
Accurate**



**LC- Loose Coupling
Methods**



- In both methods CFD is computed time accurately
- In TA, airload $\{f(t-1)\}$ is from previous CFD time step for explicit time integration with CSD. Same time step is used both for CFD and CSD

$$[m]\{\ddot{q}\} + [c]\{\dot{q}\} + [k]\{q\} = \{f_{CFD}\}$$

- In LC, $\{\bar{f}\}$ is modified using non-CFD (look-up tables!)

$$[m]\{\ddot{q}\} + [C]\{\dot{q}\} + [k]\{q\} = \{\bar{f}\} = g(\{q\}) + \{\Delta f_{CFD}\}$$

- G is based on linear theory, look-up tables etc.
- CFD and CSD is not in the same time frame



Take-off Simulation

Assumed that all components undergo rigid body motions with or without rotations. The configuration is modeled to undergo vertical (y) and forward (x) motions and rotation about a center of mass.

T, L, D, and G are thrust, lift, drag, and gravitational forces in lbs., whereas α represents the angle of attack in degrees. The equations of motions can be written as:

$$m\ddot{x} = T\cos(\alpha) + L\sin(\alpha) - D\cos(\alpha) \quad (1a)$$

$$m\ddot{y} = T\sin(\alpha) + L\cos(\alpha) - D\sin(\alpha) - m\ddot{g} \quad (1b)$$

where m is the mass in slugs and g is acceleration due to gravity in feet per second. L and D can be expressed as $1/2rV^2 SC_l$ and $1/2rV^2 SC_d$, where S is the surface area, r is air density in slugs per ft³, and V is velocity in feet per second. C_l and C_d are lift and drag force coefficients.

Assuming a small angle of attack and defining the following:

$$\cos(\alpha) = \frac{\dot{x}}{\sqrt{\dot{x}^2 + \dot{y}^2}} = \frac{\dot{x}}{V} \quad ; \quad \sin(\alpha) = \frac{\dot{y}}{\sqrt{\dot{x}^2 + \dot{y}^2}} = \frac{\dot{y}}{V}$$



Take-off Simulation (Continued)

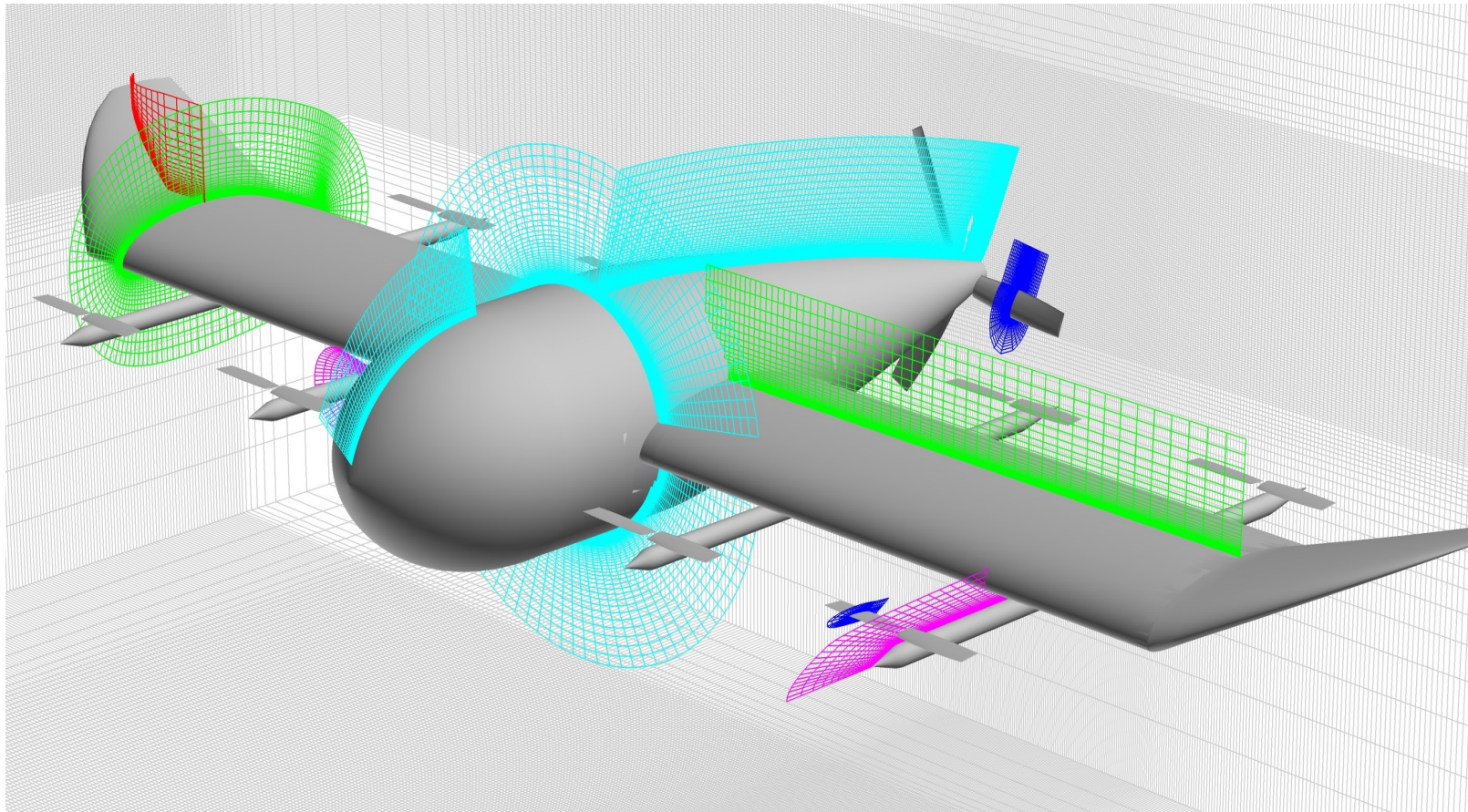
Eq (1) can be written as:

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{Bmatrix} \ddot{x} \\ \ddot{y} \end{Bmatrix} + p \begin{bmatrix} C_d & C_l \\ -C_l & C_d \end{bmatrix} \begin{Bmatrix} \dot{x} \\ \dot{y} \end{Bmatrix} = \begin{Bmatrix} 0 \\ -g \end{Bmatrix} + \frac{1}{m} \begin{Bmatrix} T \\ 0 \end{Bmatrix} \quad (2)$$

where $p = rVS/2m$.

Equations (2) are solved time-accurately by using the Newmark Time Integration Scheme.

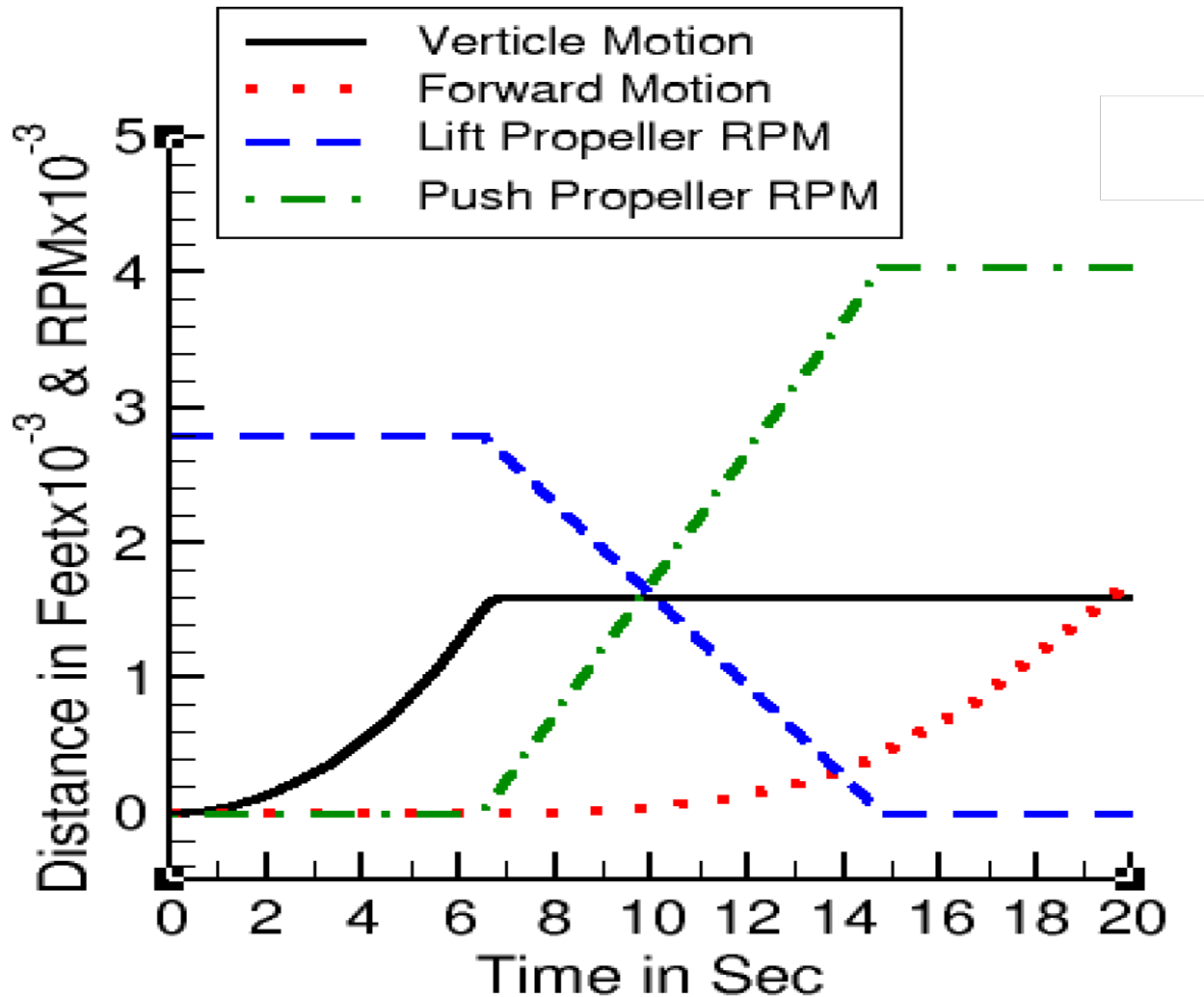
The aerodynamic quantities C_l , C_d , and T are computed by solving RANS equations with the OVERFLOW code and are used to solve Eqs. (2) at every step. The rigid body motions from Eqs. (2) are fed back to OVERFLOW code using interface data files.





Take-off Simulation (Continued)

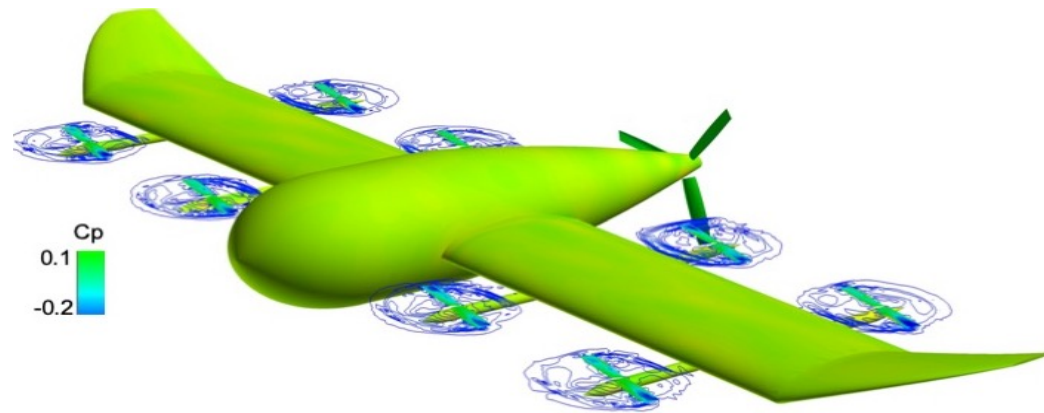
Trajectory response for vertical and forward motion



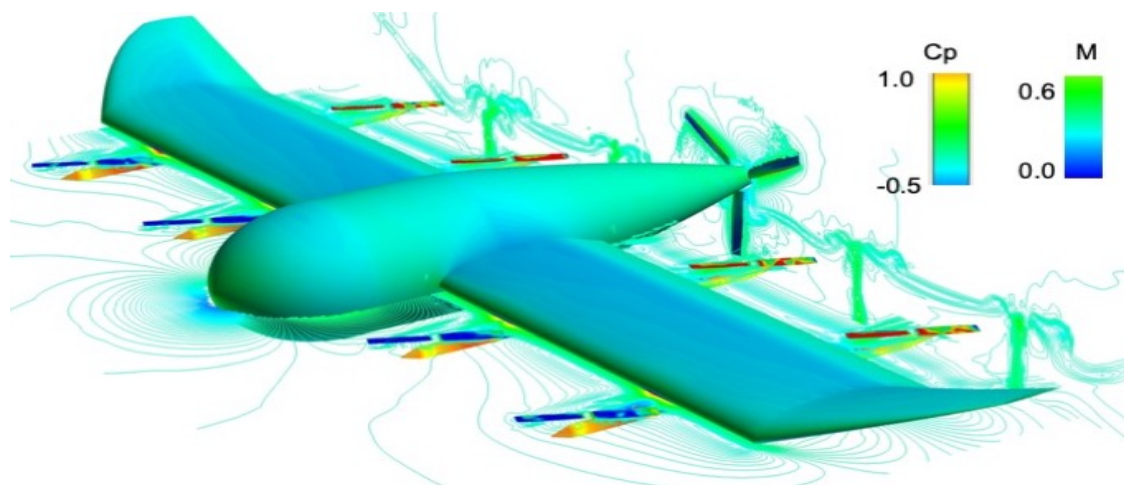


Take-off Simulation (Continued)

Surface Cp and Field Mach Number Distributions During Vertical Take-off.



Surface Cp and Field Mach Number Distributions During Forward Motion





Take-off Simulation (Continued)



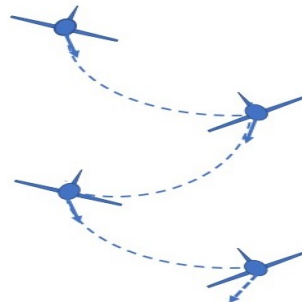
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Dutch-Roll Oscillations

Air taxis often face unexpected wind conditions, especially in windy cities like Chicago, that can lead to undesirable motions such as Dutch-roll oscillations.

Dutch-roll response consists of a combined rolling, side slipping, and yawing motion, Dutch-roll is a series of out-of-phase turns, when the aircraft rolls in one direction and yaws in the other. When the right-wing rolls-up due to higher lift, the aircraft yaws to the right due to the higher drag of the right wing typically associated with higher lift. For aircraft with vertical tails, this motion continues until the yaw angle reaches the point where the vertical stabilizer effectively becomes a wind vane and reverses the yawing motion. As a result, the aircraft yaws back to the left.





Dutch-Roll Oscillations (Continued)

High-wing is chosen instead of the mid-wing used in the previous study for many advantages such as:

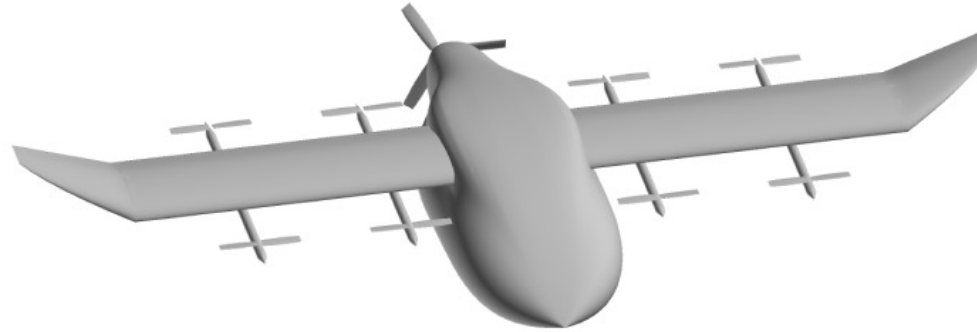
- i. A high-wing eases and facilitates the entrance and exit of passengers.**
- ii. It facilitates the installation of propellers on the wing, since the propeller clearance is higher (and safer), compared with low-wing configuration.**
- iii. It facilitates stability since the aircraft center of gravity is lower than the wing.**
- iv. There is a lower possibility of human accident to hit the propeller and be pulled to the engine inlet.**
- v. There is more space inside fuselage for cargo, luggage, or passengers since wings are located above fuselage.**

The main issue of high-wing is that the aircraft lateral control is weaker compared with mid-wing. However, the issue can be addressed using active controls

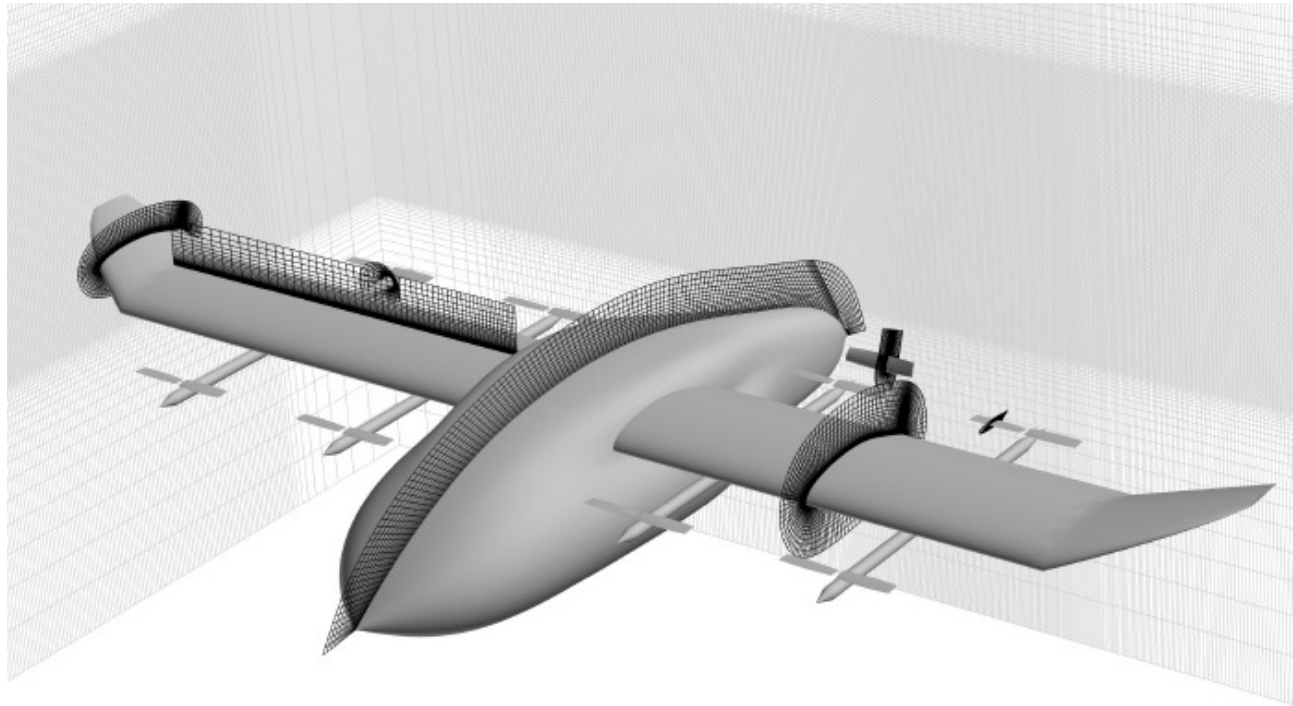
(A transport aircraft experienced severe Dutch-Roll oscillation from Flight to Oakland July 2024)



Dutch-Roll Oscillations (Continued)



High Wing Air Taxi



Overset Grid for High Wing Air Taxi



Dutch-Roll Oscillations (Continued)

Dutch roll equations derived by Banner and Kuhl based on assumptions

- the angle of attack at which the oscillation initiated is constant
- moderate angles of attack α ($\sin \alpha \sim \alpha$, $\cos \alpha \sim 1.0$)
- XZ product of inertia is negligible.

Defining p and r as roll and yaw rates, respectively, reduces the lateral-directional equations to

$$\dot{p} = \frac{L_{\beta} \beta}{I_x} \quad (1 \text{ a}). \quad \dot{r} = \frac{N_{\beta} \beta}{I_z} \quad (1 \text{ b})$$

$$\dot{\beta} = -r + \alpha_0 p \quad (1 \text{ c})$$

Then taking the time derivative of the $\dot{\beta}$ equation (1 c):

$$\ddot{\beta} = -\dot{r} + \alpha_0 \dot{p} \quad (2)$$

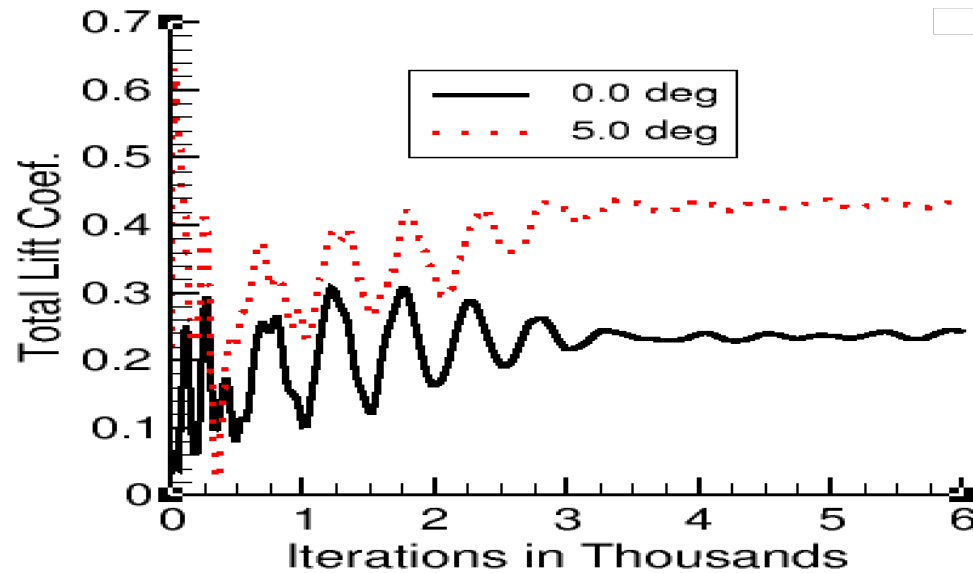
$$\ddot{\beta} + \left(\frac{N_{\beta}}{I_z} - \alpha_0 \frac{L_{\beta}}{I_x} \right) \beta = 0.0 \quad (3)$$

where L and N are rolling and yaw moments, respectively; I_x and I_y are moments of inertia about x and z axis, respectively; and initial angle of attack is represented by α_0 .

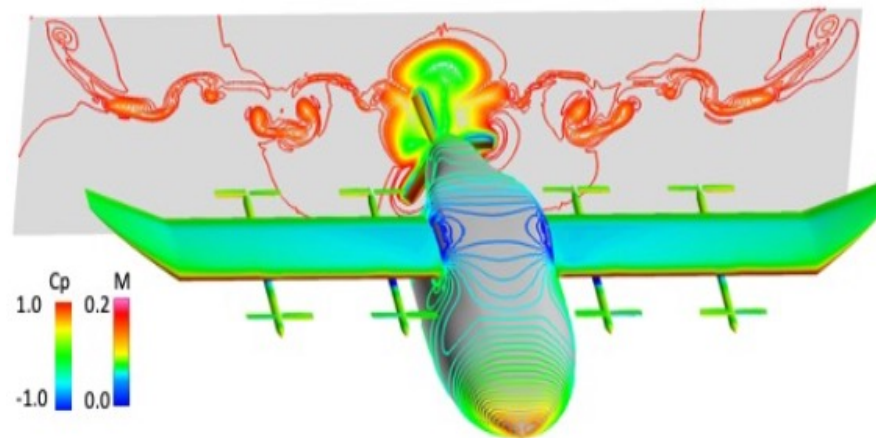


Dutch-Roll Oscillations (Continued)

Convergence of total lift coefficients at $M_\infty = 0.20$.



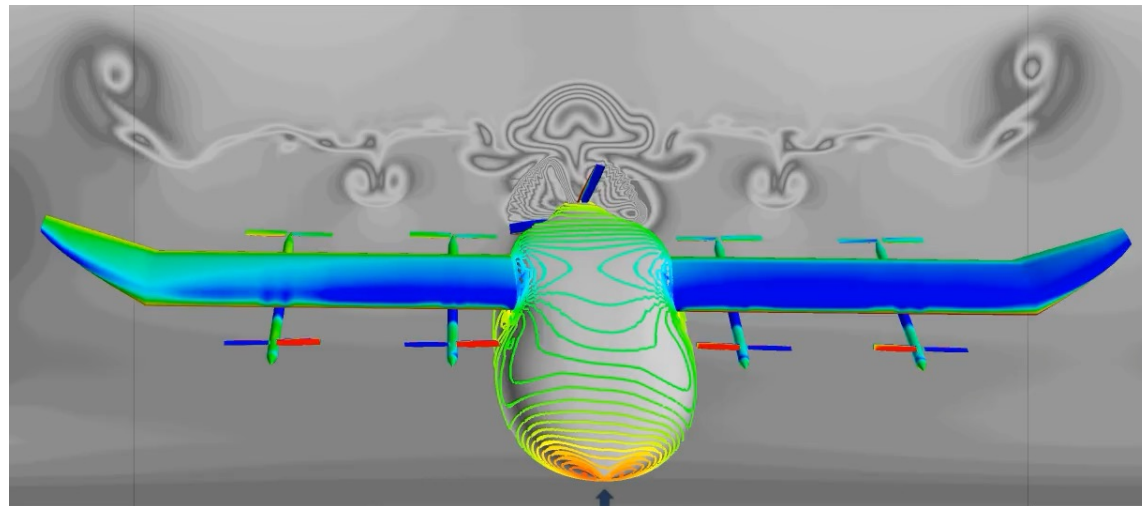
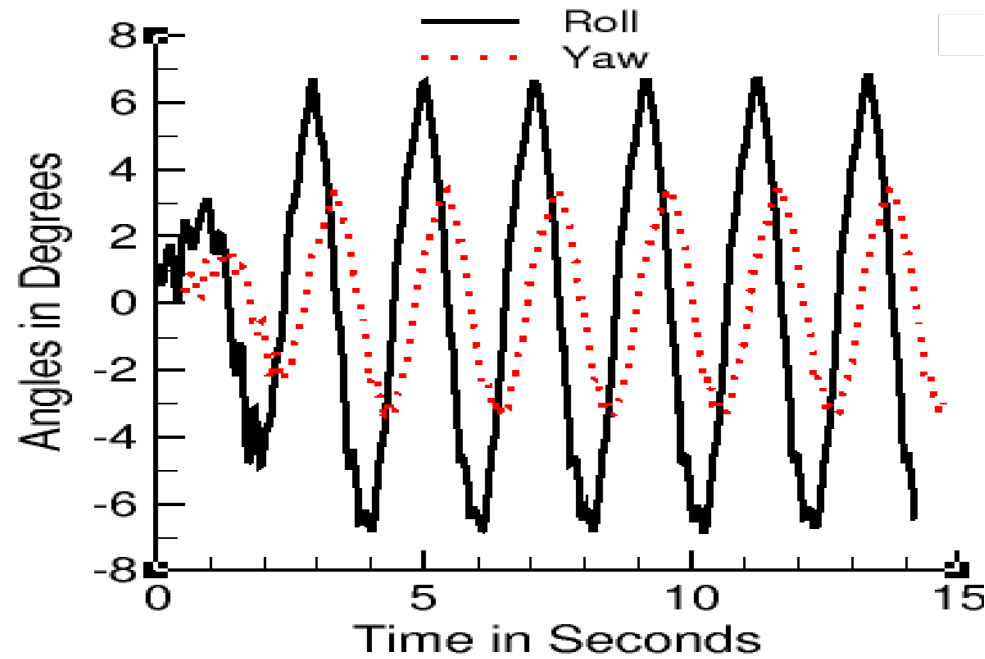
Surface C_p and field M distributions at $M_\infty = 0.20$ and $\alpha = 0$ deg





Dutch-Roll Oscillations (Continued)

Roll and yaw responses during Dutch roll oscillations at $M_\infty = 0.20$.



MOVIE



Active Control of Dutch-Roll Oscillations

- **Objective**
 - **Develop a procedure to accurately simulate the use of existing propellers to suppress oscillations**
- **Approach**
 - **Identify accurate flow simulation tool**
 - **Simulate a typical instability scenario such as Dutch-Roll oscillations**
 - **Develop feed back control simulation process to design a system to control oscillations**
 - **Demonstrate for a typical eVTOL air taxi**



Active Control of Dutch-Roll Oscillations (Continued)

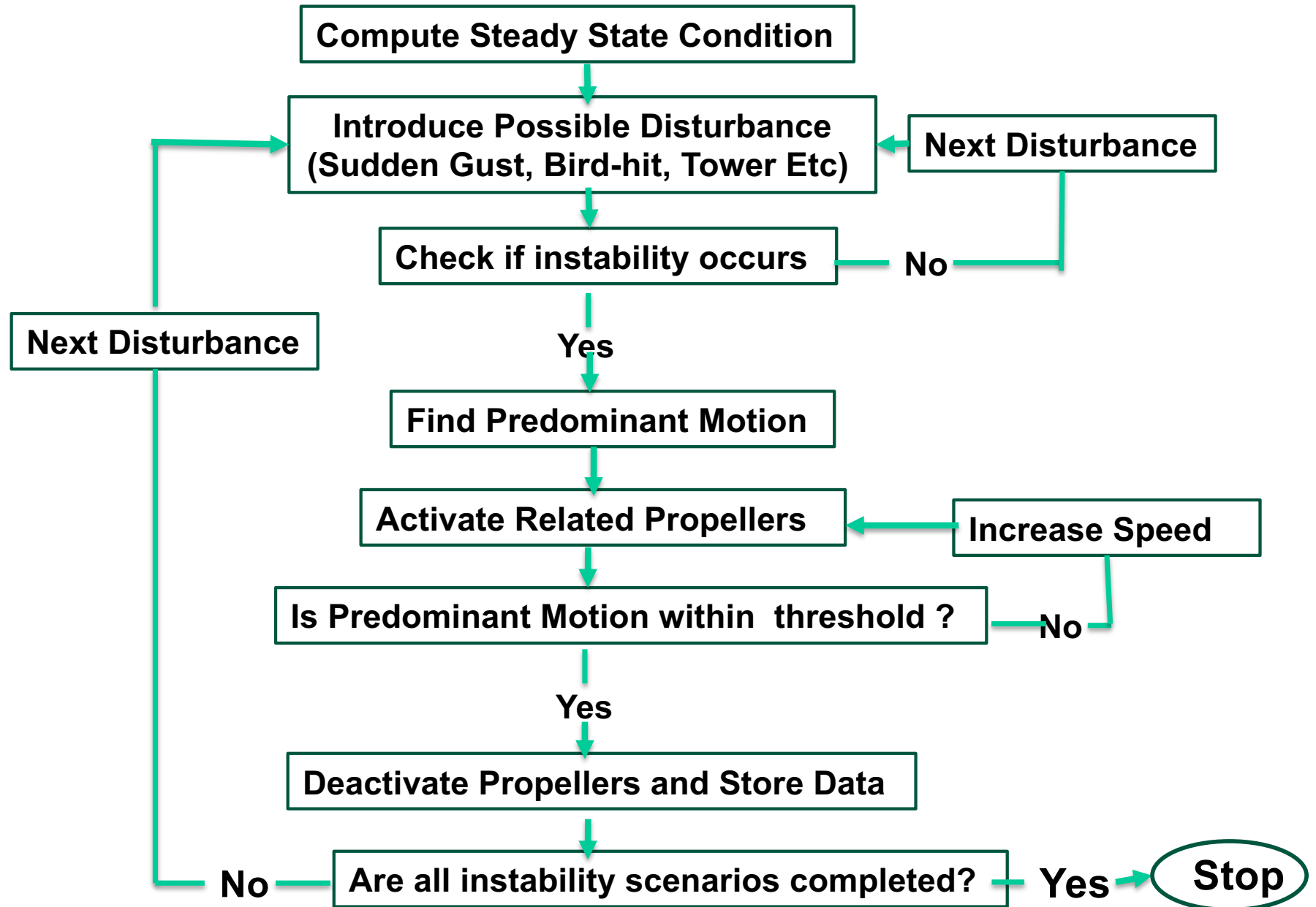
Instability Scenario

- **Pilot recognizes instability either from instrumentation or feeling**
- **Triggers instrumentation that identifies which motion is predominantly excited and/or identifies by feeling**
- **Turns-on control system that is pre-designed to suppress that oscillation**
- **Example – Dutch-Roll oscillations**
 - **Uncontrolled coupled Roll/Yaw motions**
 - **If predominantly roll motion trigger lifting propellers**
 - **If predominantly yaw motion tune pushing propellers**
- **Above needs calibration of propeller speeds vs amplitude of motions**
 - **Flow is complex due to presence of multiple propellers**
 - **Needs flow simulation software such as OVERFLOW**
 - **Need supercomputer to calibrate for various scenarios of atmospheric disturbances, bird-hit instabilities etc**



Active Control of Dutch-Roll Oscillations (Continued)

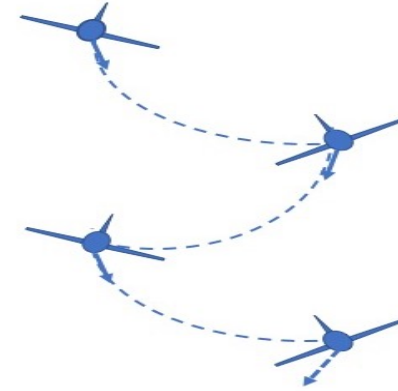
Generate Calibration Data for Active Control System





Typical instability –Dutch-Roll Oscillations

- Dutch-roll is a series of out-of-phase turns, when the aircraft rolls in one direction and yaws in the other
- When the right-wing rolls-up due to higher lift, the aircraft yaws to the right due to the higher drag of the right wing typically associated with higher lift
- Dutch-roll equation derived by Banner and Kuhl of NASA is used



$$\ddot{\beta} + \left(\frac{N_{\beta}}{I_z} - \alpha_0 \frac{L_{\beta}}{I_x} \right) \beta = 0.0 \quad (1)$$

where L and N are rolling and yaw moments, respectively; I_x and I_z are moments of inertia about x and z axis, respectively; β is side slip angle; and the angle of attack is represented by α_0 . L_{β} and N_{β} are rates of change of roll and yaw moments with respect to sideslip β , respectively. By solving Eq. (1) with time integration, p and r as roll and yaw rates computed using:

$$\dot{p} = \frac{L_{\beta} \beta}{I_x} \quad (2a) \quad \dot{r} = \frac{N_{\beta} \beta}{I_z} \quad (2b)$$

Guruswamy , G.P. "[Dutch-Roll Stability Analysis of an Air Mobility Vehicle Using Navier–Stokes Equations](#)," AIAA JI, Vol. 59, No. 10 (2021)



Active Control of Dutch-Roll Oscillations (Continued)

Active Control Strategy

- During cruise it is assumed that the lifting propellers are stationary.
- Outboard propellers of wing in downward motion rotated at a speed proportional to the roll angle to counter the roll moments
- The rotational speed of the blades in revolution per minute (RPM) Ω is defined for right and left wings as

$$\Omega = C \times \phi$$

Where ϕ is roll angle in radians. C is defined as $L/(d \times R)$, where L is the roll moment, d is the distance of outboard propellers from the fuselage center line, and R is rate of change of thrust from active propellers with respect to RPM. The coefficient R is assumed to linear vary with RPM

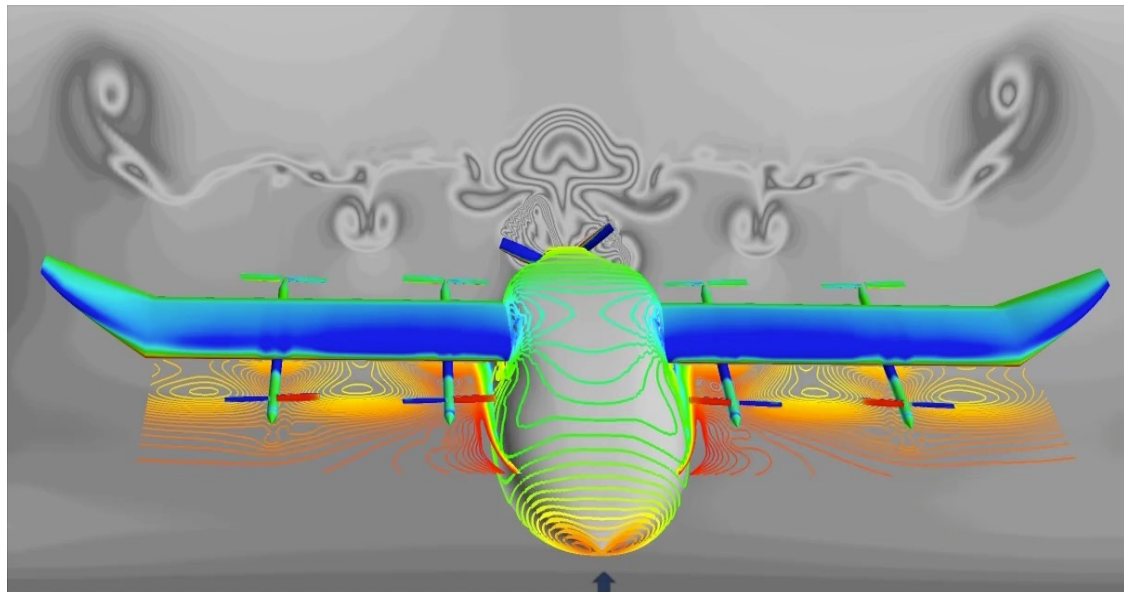
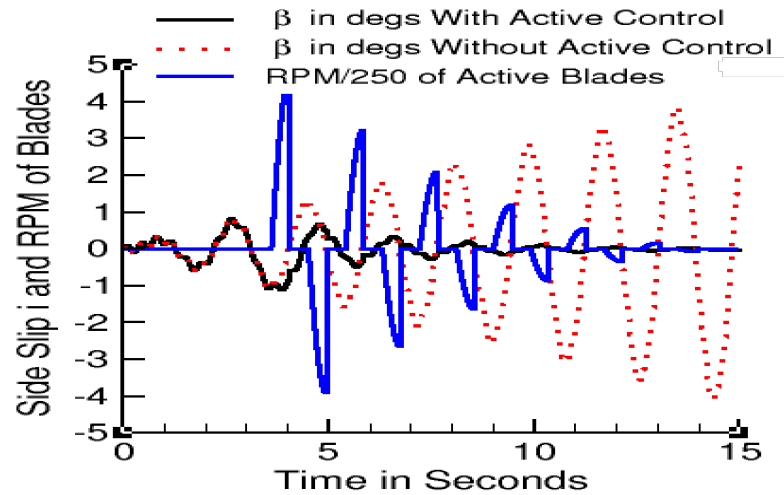
- In OVERFLOW, the rotating speed of blades are prescribed through input 'Scenario.xml'. In order to facilitate the change in RPM at every step, a script is written for the code to run in restart mode after each step. The RPM is computed using the roll moment L outputted by code every step and it is inputted to next step through interface 'Scenario.xml'

[Guruswamy , G.P. "Active Control of Dutch-roll Oscillations of eVTOL," Aerospace Science and Technology, Volume 119, Dec 2021.](#)



Active Control of Dutch-Roll Oscillations (Continued)

Demonstration of Suppression of Dutch-Roll Oscillations



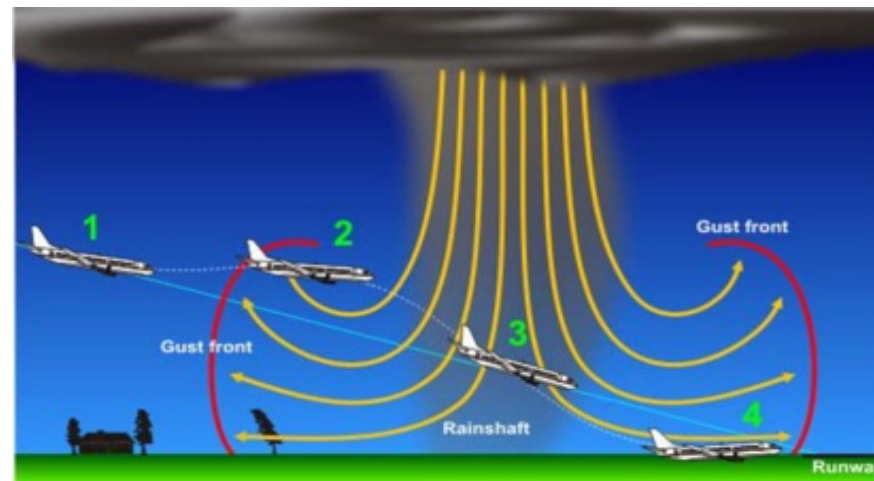
MOVIE



Gust Induced Responses

- Air taxis often face unexpected gusty wind conditions
- Gust encounters can be among the most critical load conditions that an air taxi can experience during its service.
- Lower weight of air taxi which results in an increased sensitivity to gust loads compared to conventional transport aircraft.
- For safety and comfort need suppress structural oscillations caused by gust loads rapidly by using active control methods.

Microbursts from thunderstorms produce winds ~ 100 Knots.



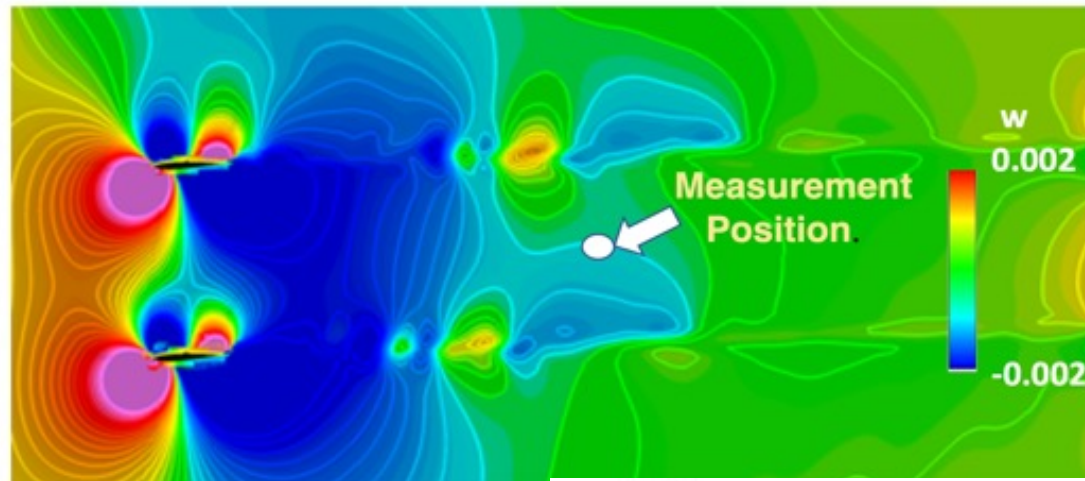


Gust Induced Responses (Continued)

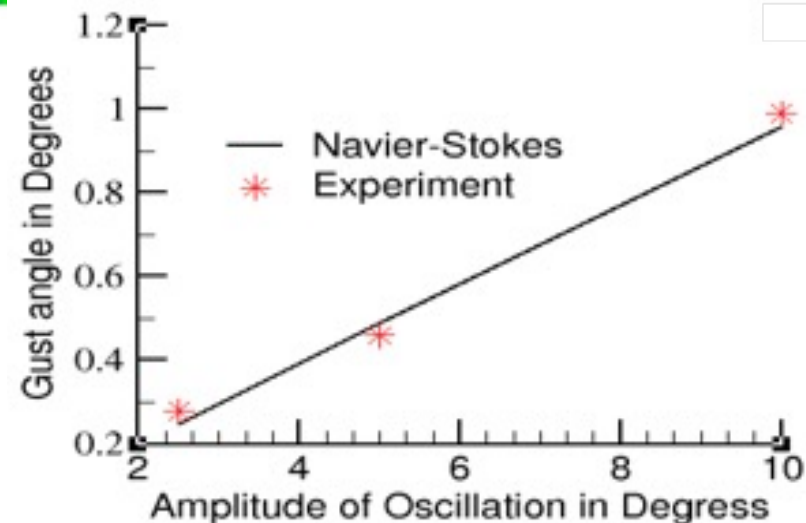
Validation With Experiment

Reduced frequency $k (\omega c/U) = 0.3768$; wind speed of 25m/sec (82 feet/sec) and vanes of length 0.3m (1ft) located 0.7 m (2.3ft) apart is selected. Vanes are embedded in a background grid of spacing 1/20 the of the chord length,

Vertical velocity distribution due to gust generated by oscillating vanes.

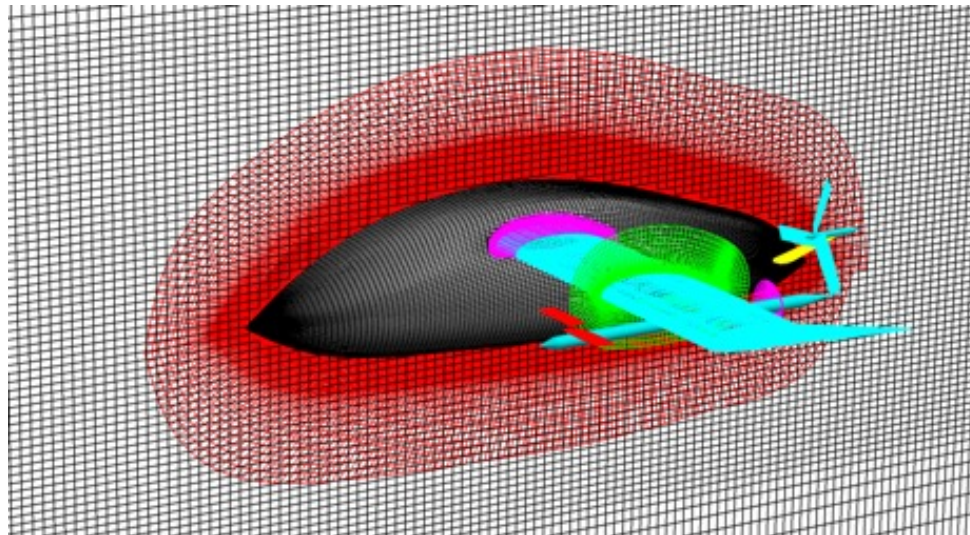
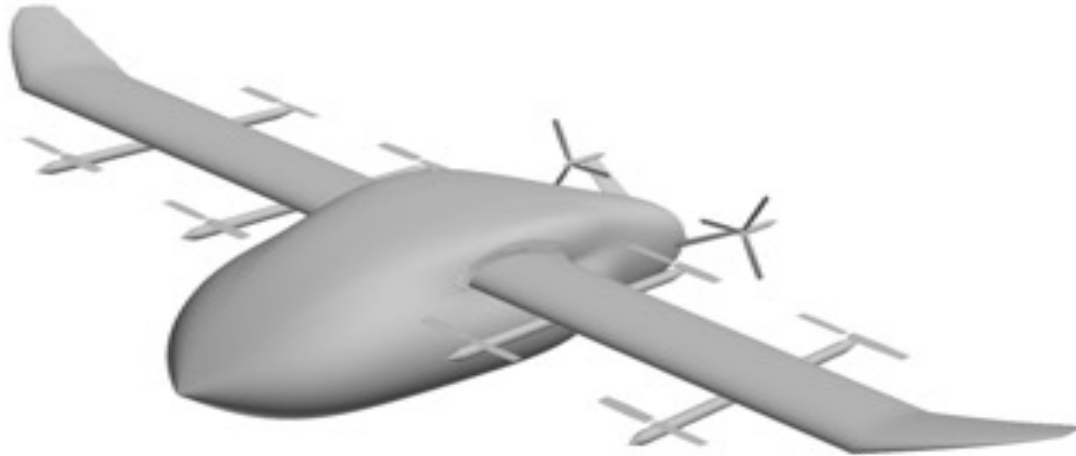


Gust angles $\alpha_g = \tan^{-1}(V_g/U)$, where V_g and U are vertical velocity induced by gust and freestream velocity, respectively.





Gust Induced Responses (Continued)

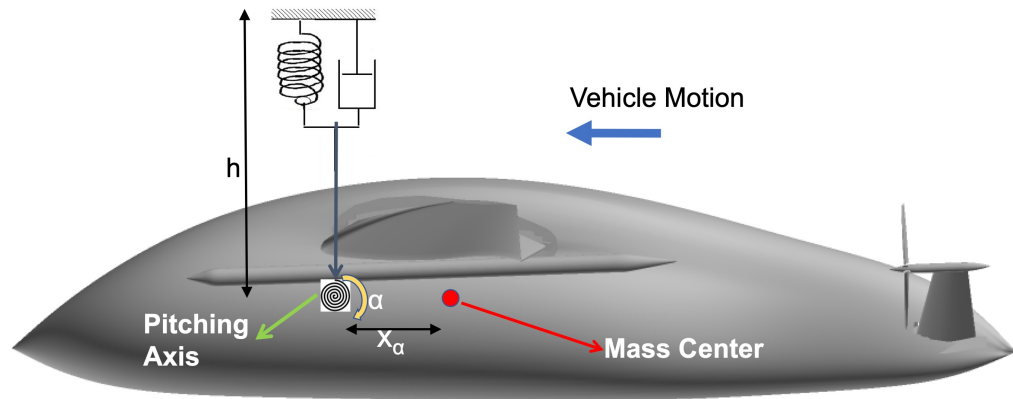




Gust Induced Responses (Continued)

Two Degree of Freedom System

It is assumed that the vehicle undergoes rigid body plunge and pitch motions



$$[P]\ddot{d} + [C]\dot{d} + [K]d = \{F\} \quad (1)$$

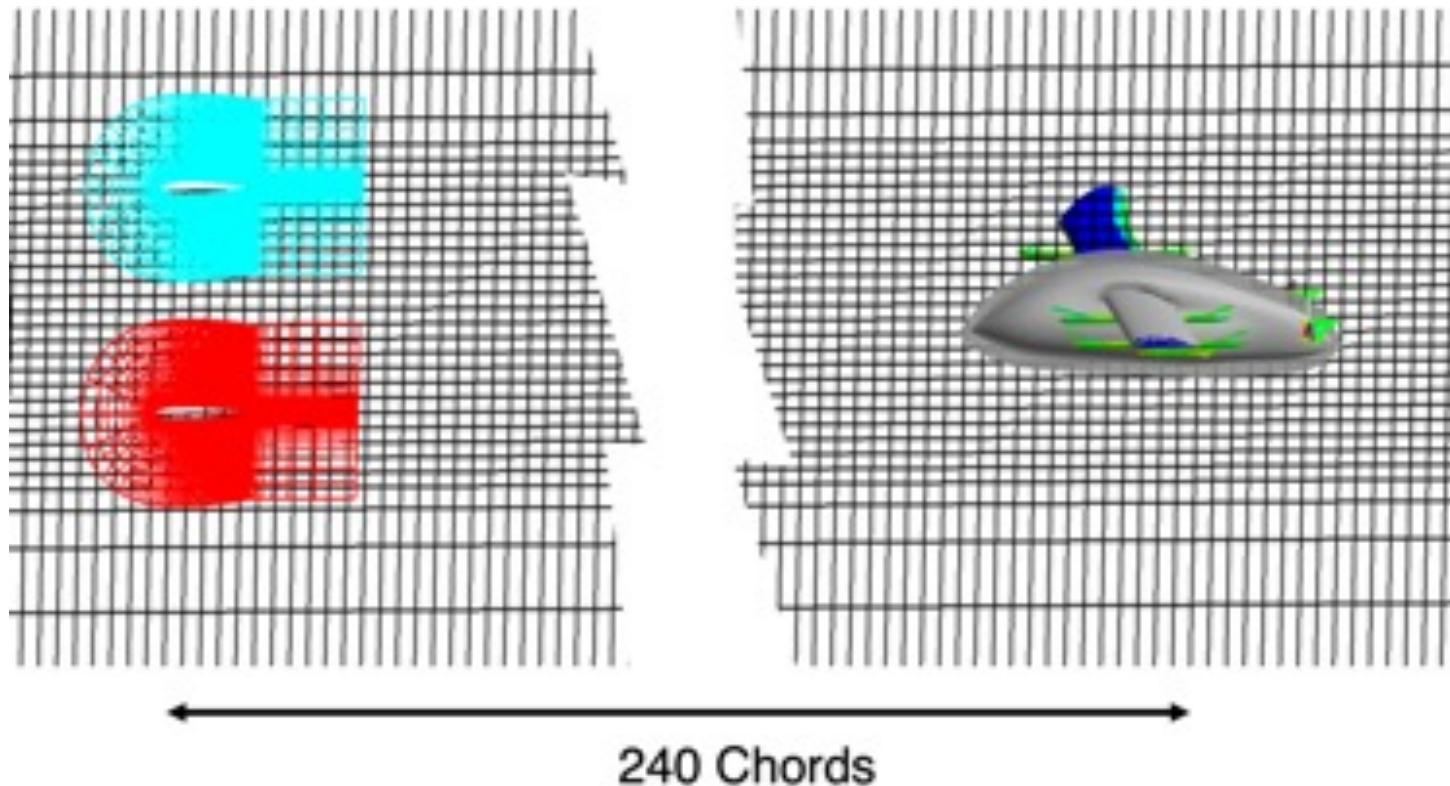
where $[P]$, $[C]$, and $[K]$ are mass, damping, and stiffness matrices, and $\{d\}$ and $\{F\}$ are the displacements and aerodynamic force vectors, respectively. The variables are defined as follows

$$[P] = \begin{bmatrix} m & mx_\alpha \\ mx_\alpha & I_\alpha \end{bmatrix}; [C] = \begin{bmatrix} c_h & 0 \\ 0 & c_\alpha \end{bmatrix}; [K] = \begin{bmatrix} k_h & 0 \\ 0 & k_\alpha \end{bmatrix}; \{d\} = \begin{Bmatrix} h \\ \alpha \end{Bmatrix}; \{F\} = \begin{Bmatrix} Q_h \\ Q_\alpha \end{Bmatrix}$$



Gust Induced Responses (Continued)

Location of vanes from the start position of a high-wing air taxi.

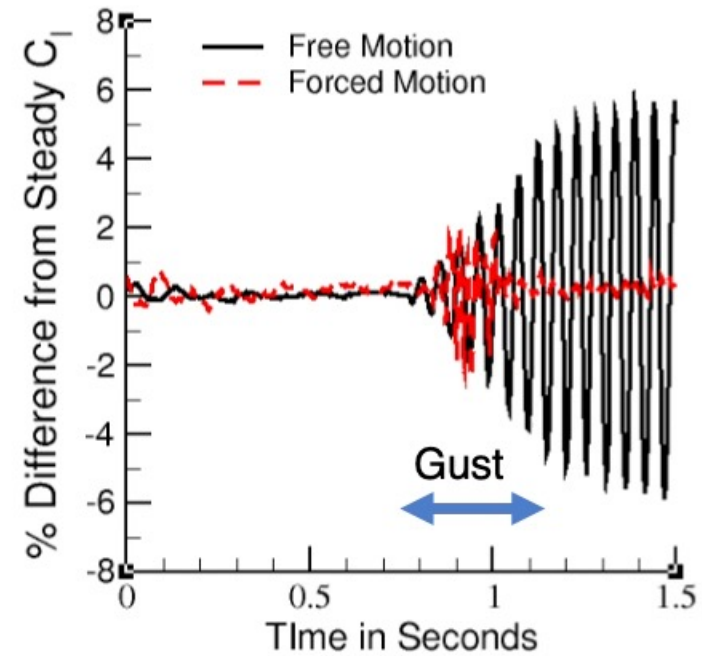
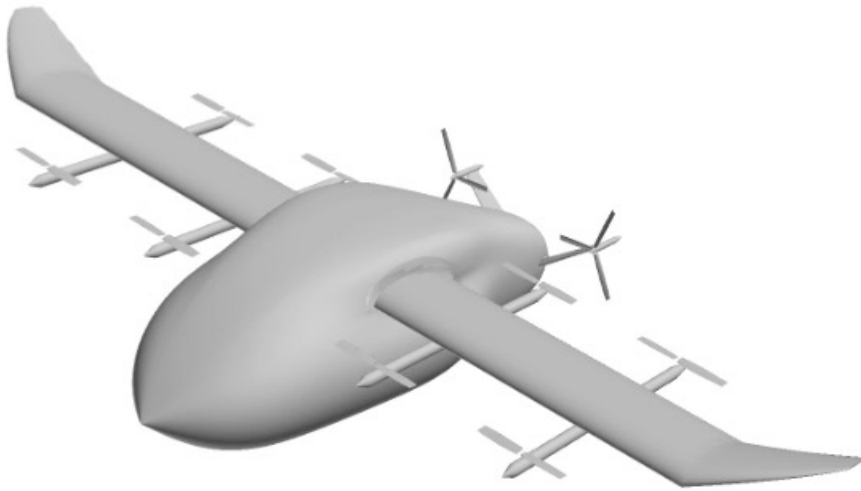


Span (b) = 30 feet; Chord (c) 3.5 feet; Length(l) 17.5 ft; Weight = 1,600lbs. Wing area (A) = 105 sqft; $I_{\alpha} = 1350 \text{ lb-ft-sec}^2$; Altitude = 2,000 feet; cruise speed of 200 ft/sec. It is assumed there is a head wind of 20 ft/sec. Plunging and pitching stiffnesses are assumed, corresponding to 2 and 5 Hz frequencies, respectively. The pushing propellers are allowed to rotate at 2,800 RPM.



Gust Induced Responses (Continued)

Air Taxi Exposed to Wind Gust



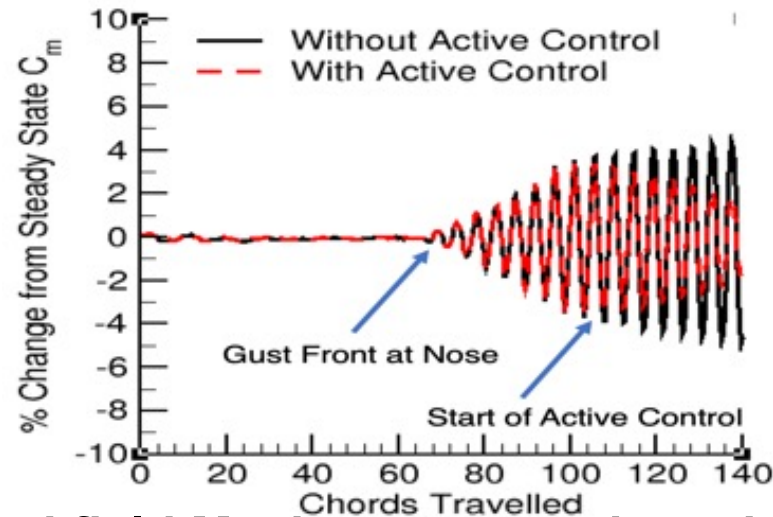
Following Movie Shows Vertical Velocity Flow Field and Surface Pressures



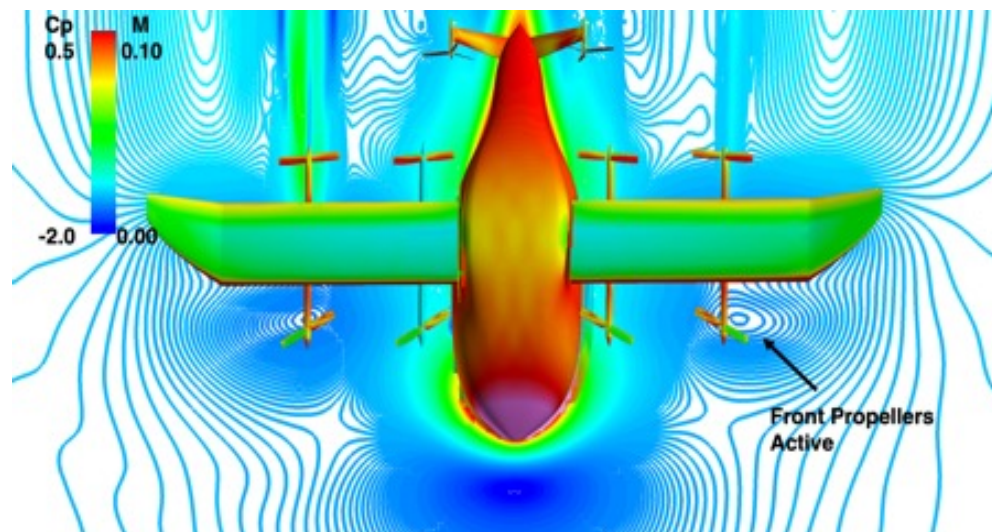
Gust Induced Responses (Continued)

Suppression of Oscillations

Moment responses with and without active controls.



Surface C_p and field Mach contours when air taxi is pitched down.





Parachute Deployment for Failed Propulsion System

Background:

- Air Taxis use Electric and Hydrogen Propulsion Systems
- Need Safety Mechanism for Failed Propulsion
- Use of Parachute is considered for Safe Descent

Approach:

- A Body Fitted Structured Grid System is Generated for a Air taxi with Parachute
- A Module is developed to Parachute Movement while Deploying
- A Framework is Built to Embed in OVERFLOW

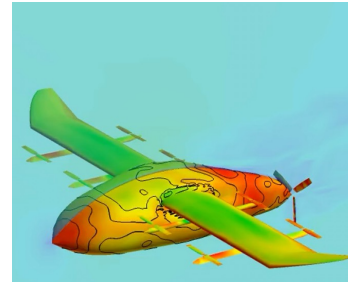
Accomplishment:

- Prescribed Deployment of Parachute after the Pushing Propeller stalls is Simulated

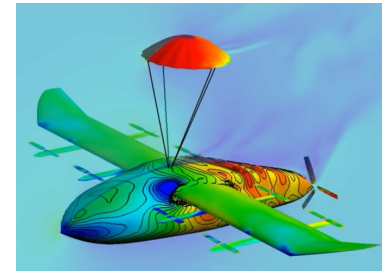
Future:

- Couple with Trajectory motion of Air Taxi with Parachute Deployment

Cruise



Propulsion Fail



MOVIE



Conclusions and Future Work

- **Procedure are presented for stability analysis of air taxis by using the state-of-the-art Navier-Stokes solvers coupled with structural equations**
- **Results are demonstrated for a typical eVTOL**
 - **Take-off simulation**
 - **Prediction of Dutch-Roll oscillations**
 - **Active Control of Lateral Instability**
 - **Effect of gust on flight**
 - **A framework to simulate emergency landing with parachutes**
- **Next effort will be to couple with high order 6-DOF trajectory equations including flexibility of wings and blades**
- **Thanks for the Support From**
Pieter Buning (LaRc), William Chan (ARC), Steven Yoon (ARC)
NAS Management