Rapid Aero Modeling for Urban Air Mobility Aircraft in Wind-Tunnel Tests

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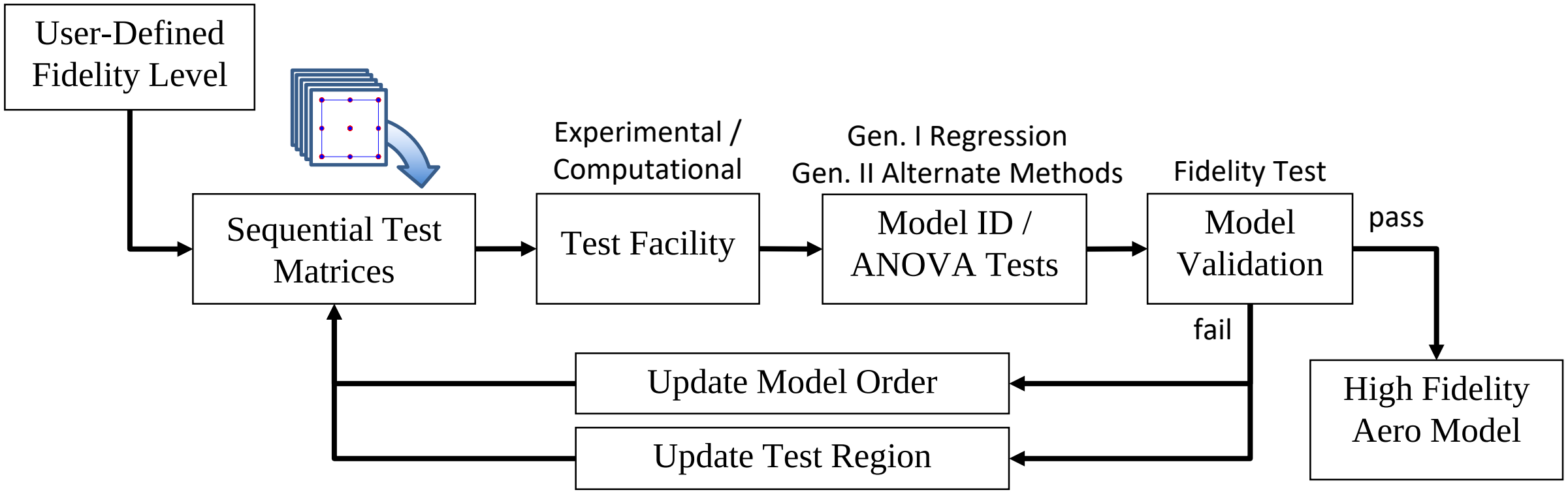
January 20, 2021

Motivation for Rapid Aero Modeling (RAM)

- Challenges in Urban Air Mobility Transportation Systems:
  - Aircraft features
    - Hybrid aircraft-rotorcraft.
    - Complexity, nonlinearity, and large numbers of interacting factors.
  - Conventional test methods (one-factor-at-a-time testing)
    - Fail to capture the complexity and numerous interactions.
    - Results in costly studies in terms of time and resources.
    - Produces models with limited information.
- Objectives:
  - Produce models suitable for nonlinear flight dynamics simulations.
  - Develop automated testing process.
  - Take advantage of well-established experiment design methods.

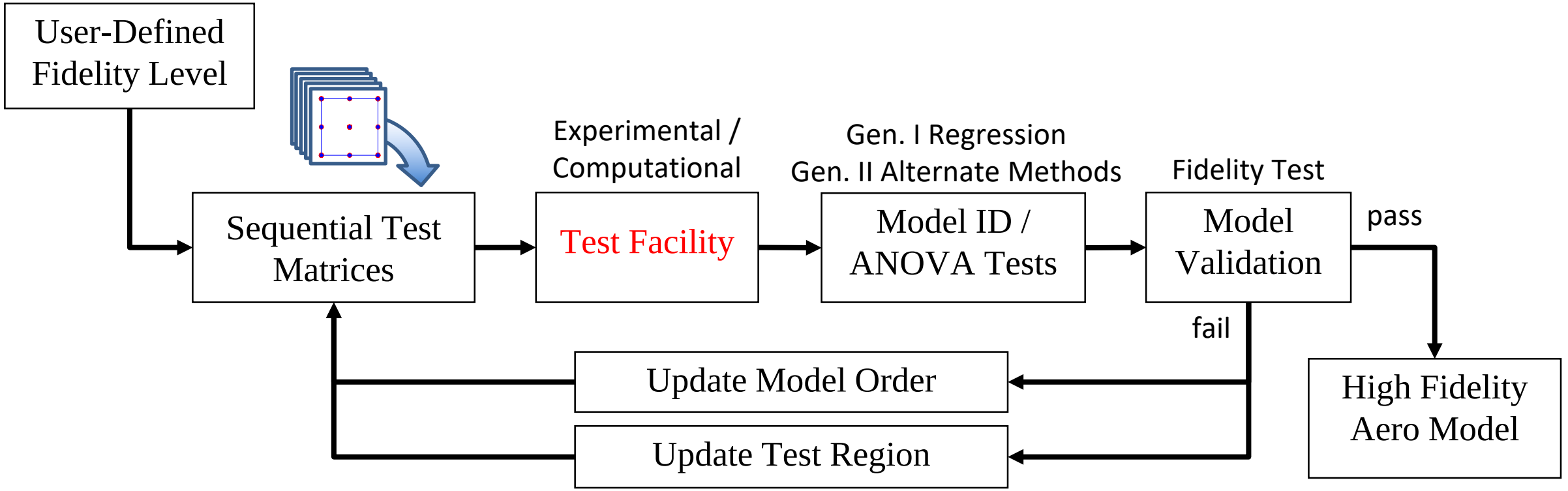
Rapid Aero Modeling (RAM) Process - Introduction

- RAM provides an automated, run efficient, statistically rigorous, testing process.
- Fidelity levels defined for each aero coefficient in terms of prediction error.



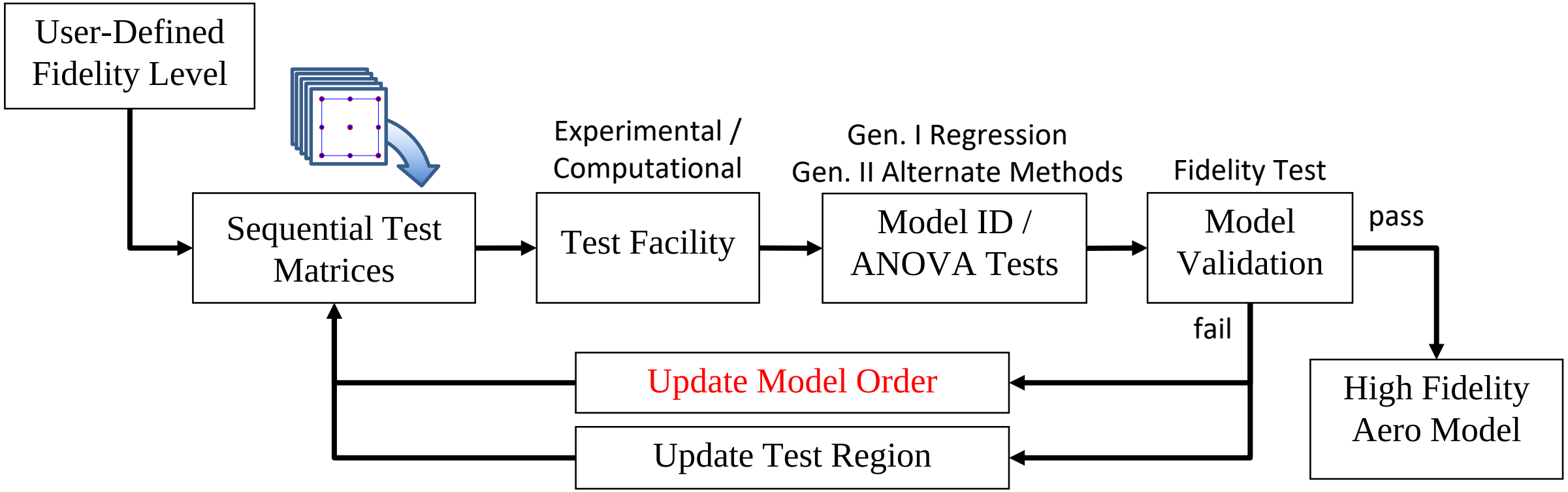
Rapid Aero Modeling (RAM) Process – Test Facilities

- First applications to static wind-tunnel (RAM-T) and computational experiments (RAM-C).



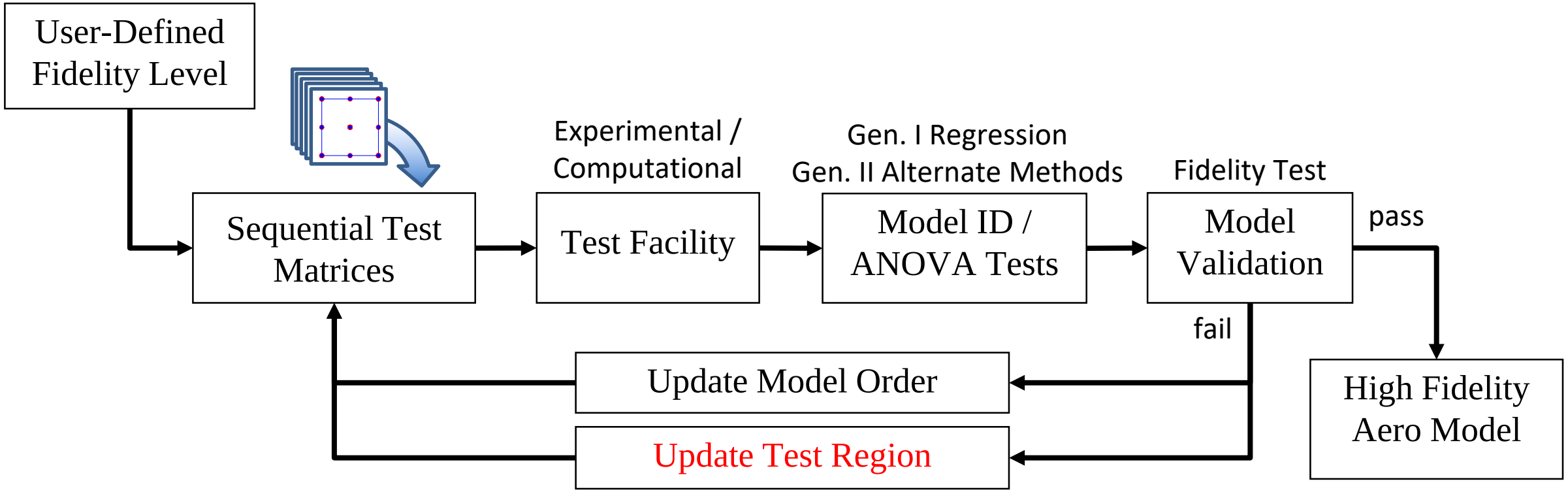
Rapid Aero Modeling (RAM) Process – Inner Loop

- New data blocks requested only as needed to satisfy more complex polynomial models.



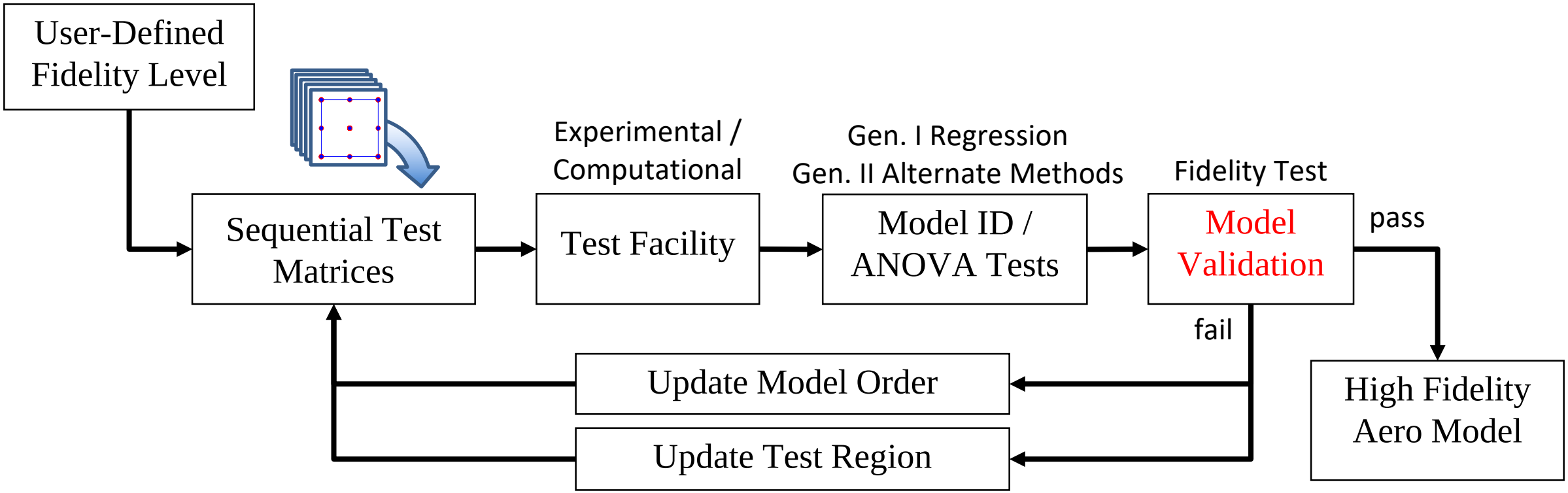
Rapid Aero Modeling (RAM) Process – Outer Loop

- Test region is split when validation fails with highest-order polynomial.



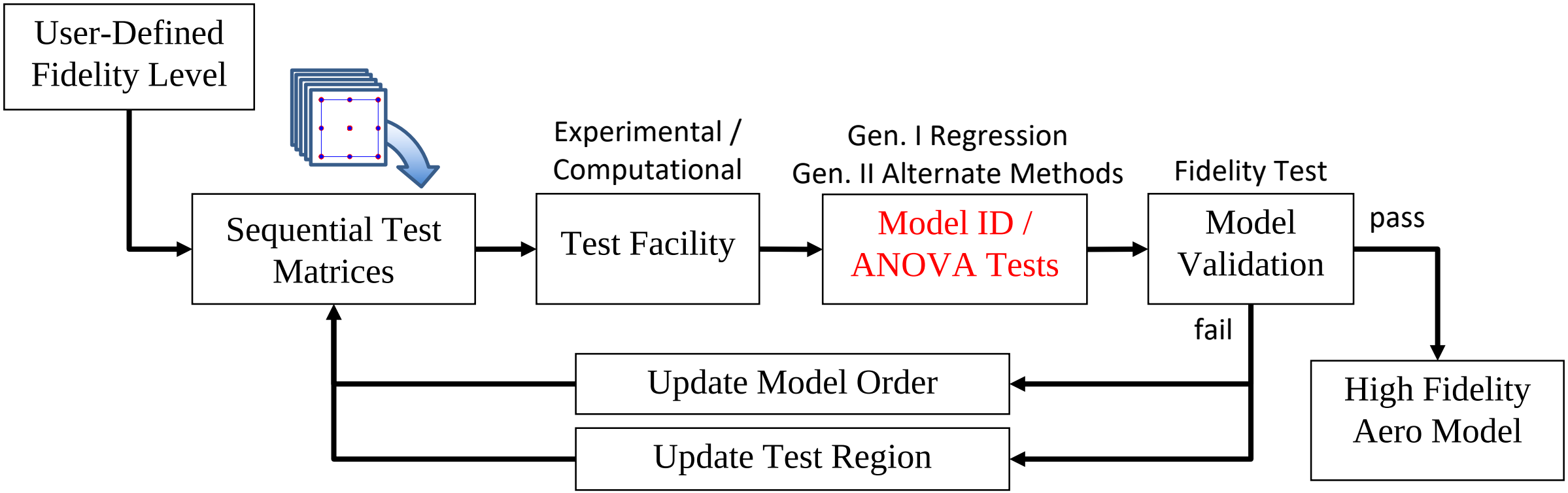
Rapid Aero Modeling (RAM) Process – Model Validation

- Data for validation are not used for model identification.



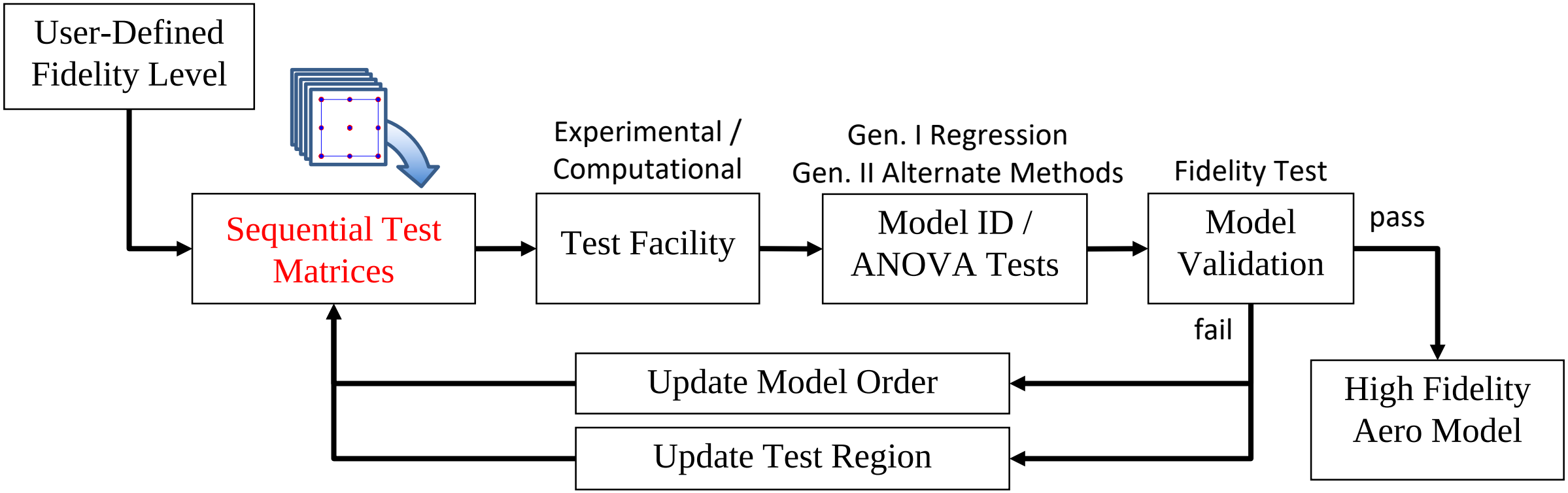
Rapid Aero Modeling (RAM) Process – Model Validation

- Stepwise regression is used for Model ID.



Rapid Aero Modeling (RAM) Process – Test Matrices

- RAM Block Library of test matrices based on DOE/RSM theory.



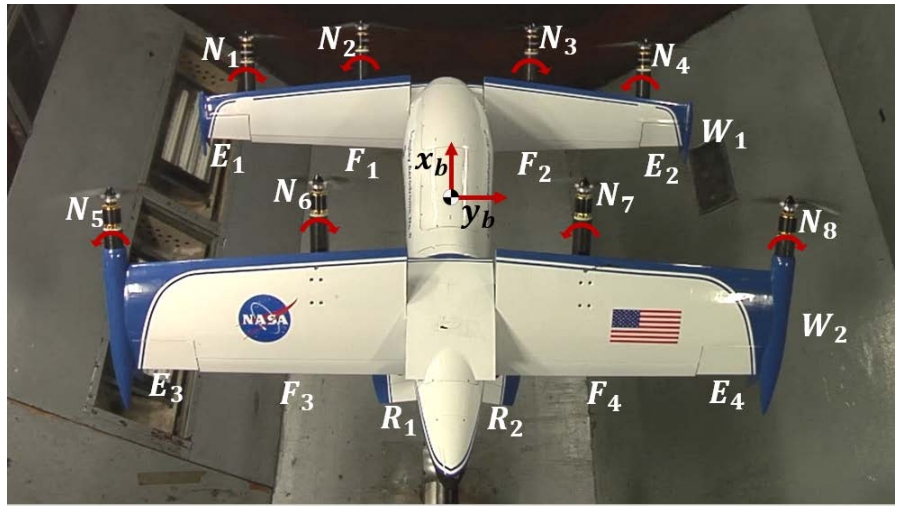
RAM-T Example Applications

- Mini E-1, 9-factor study, with data obtained from NASA Langley 12-Foot Low Speed Wind Tunnel
  - 2 wind angles: α, β
  - 7 control surfaces: LA, LF, RF, RA, LE, RE, RUD
  - conventional response variables
- LA-8, 21-factor simulated study, at q = 3.5 psf
  - 2 wind angles: α, β
  - 1 wing-tilt angle (W_1, W_2 ganged): $\delta\omega$
  - 4 flaps: F_1-F_4
  - 4 elevons: E_1-E_4
  - 2 ruddervators: R_1-R_2
  - 8 propellers: N_1-N_8

Mini E-1 Conventional Configuration



NASA LA-8 Tilt-Wing Configuration



Basic Block Designs & Supported Models – 2-factor Case

- Full factorial design

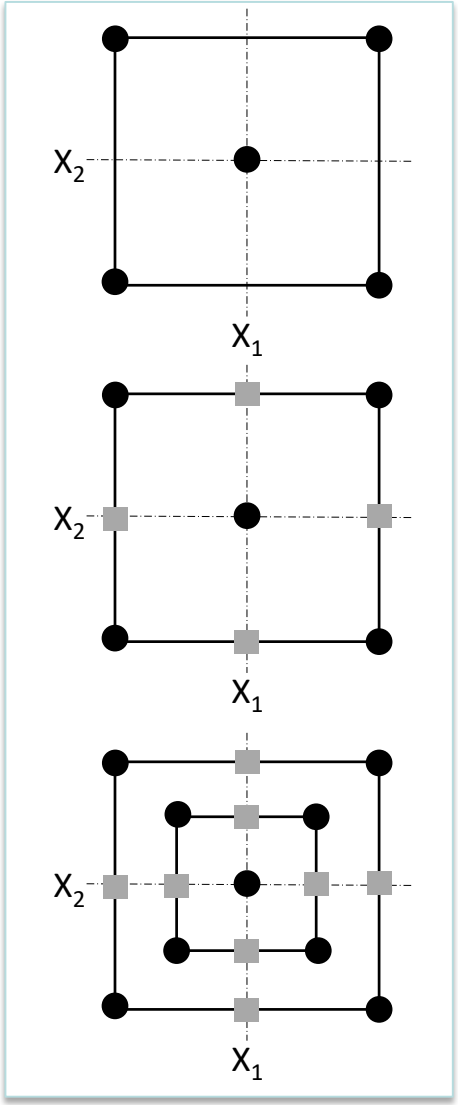
$$y = B_0 + \sum_i B_i x_i + \sum_{i \neq j} \sum B_{ij} x_i x_j + \ldots + \varepsilon \qquad i = 1, 2, \ldots, k$$

- Face-centered design (FCD) – *RAM Block #1*

$$y = B_0 + \sum_i B_i x_i + \sum_i B_{ii} x_i^2 + \sum_{i \neq j} \sum B_{ij} x_i x_j + \varepsilon \qquad i = 1, 2, \ldots, k$$

- Nested face-centered design – *RAM Blocks #1 & #2*

$$y = B_0 + \sum_i B_i x_i + \sum_i B_{ii} x_i^2 + \sum_{i \neq j} \sum B_{ij} x_i x_j + \sum_i B_{iii} x_i^3 + \varepsilon \qquad i = 1, 2, \ldots, k$$



Basic Block Designs & Supported Models – 2-factor Case

- Full factorial design

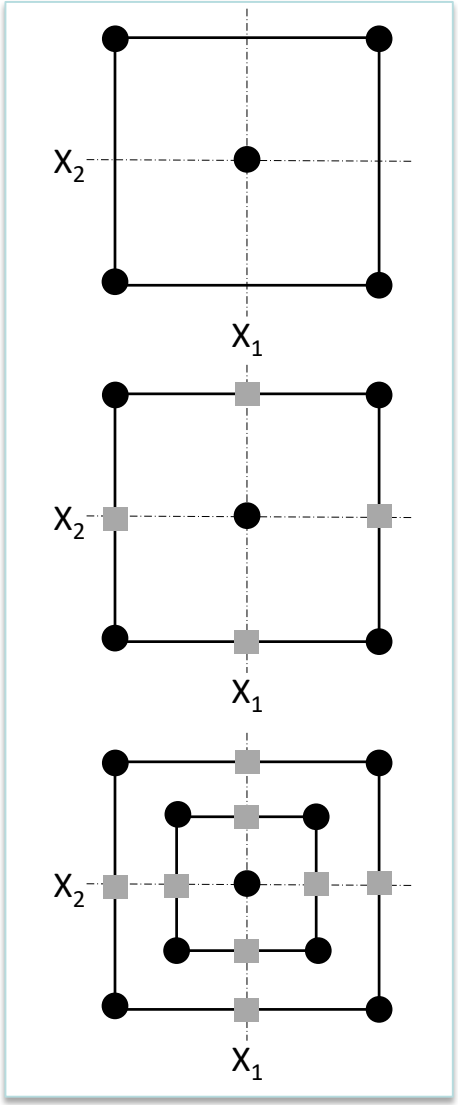
$$y = B_0 + \sum_i B_i x_i + \sum \sum_{i \neq j} B_{ij} x_i x_j + \ldots + \varepsilon \qquad i = 1, 2, \ldots, k$$

- Face-centered design (FCD) – *RAM Block #1*

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Basic Block Designs & Supported Models – 2-factor Case

- Full factorial design

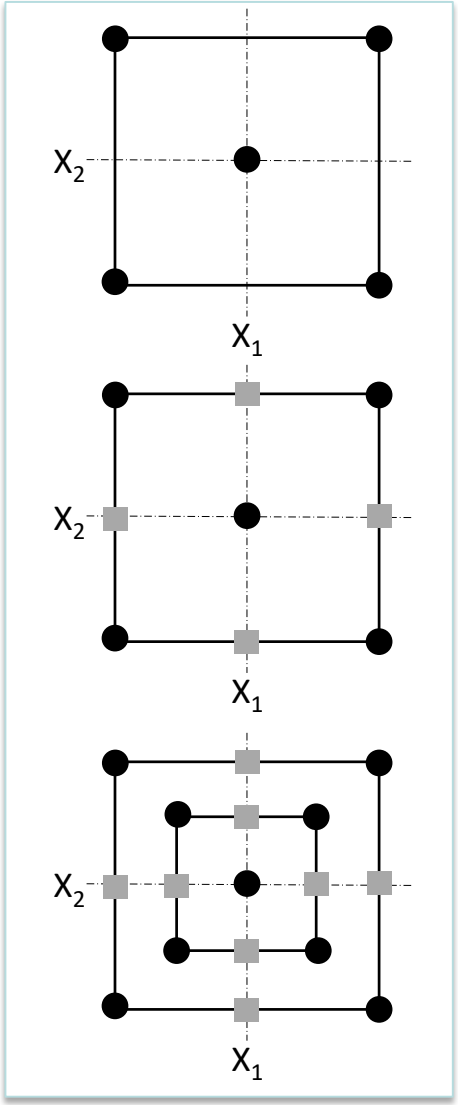
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- Nested face-centered design – *RAM Blocks #1 & #2*

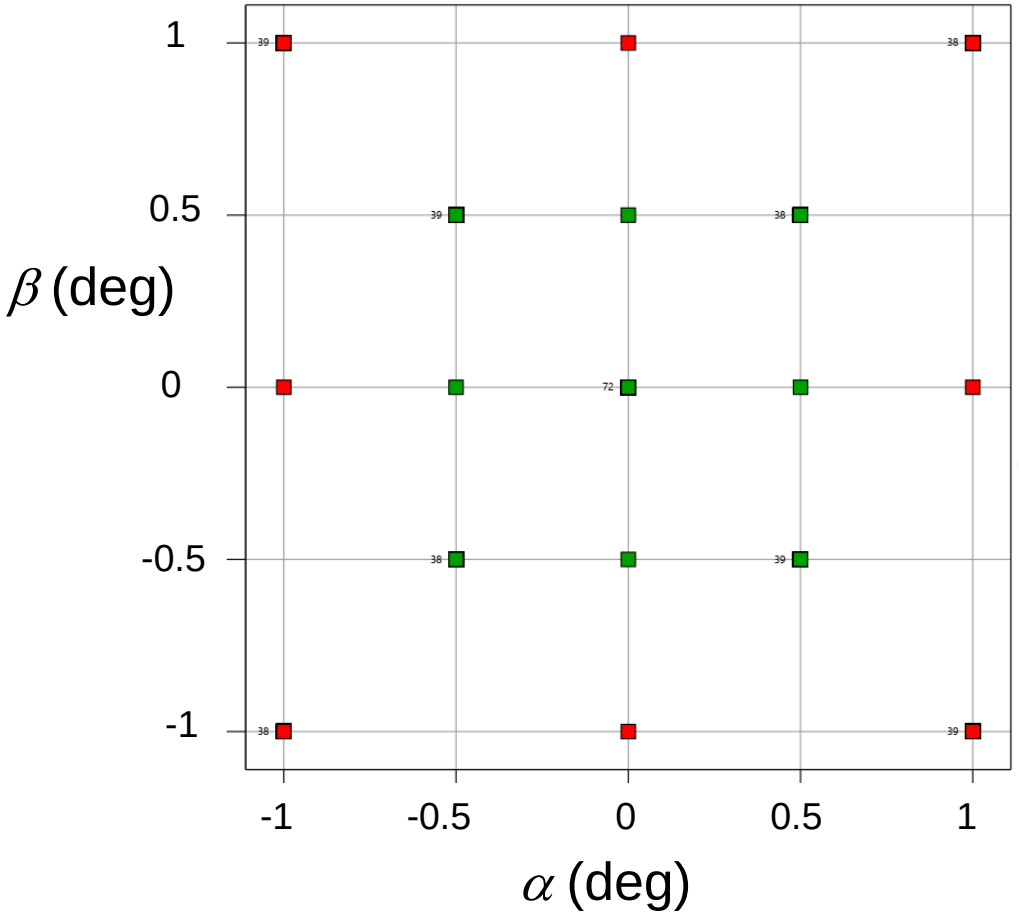
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RAM Design for LA-8, 21-factor Study

- 21 factors, 5-blocks (factors are scaled to +/- 1), 865 test points

Block 1 – FCD
Block 2 – nested FCD

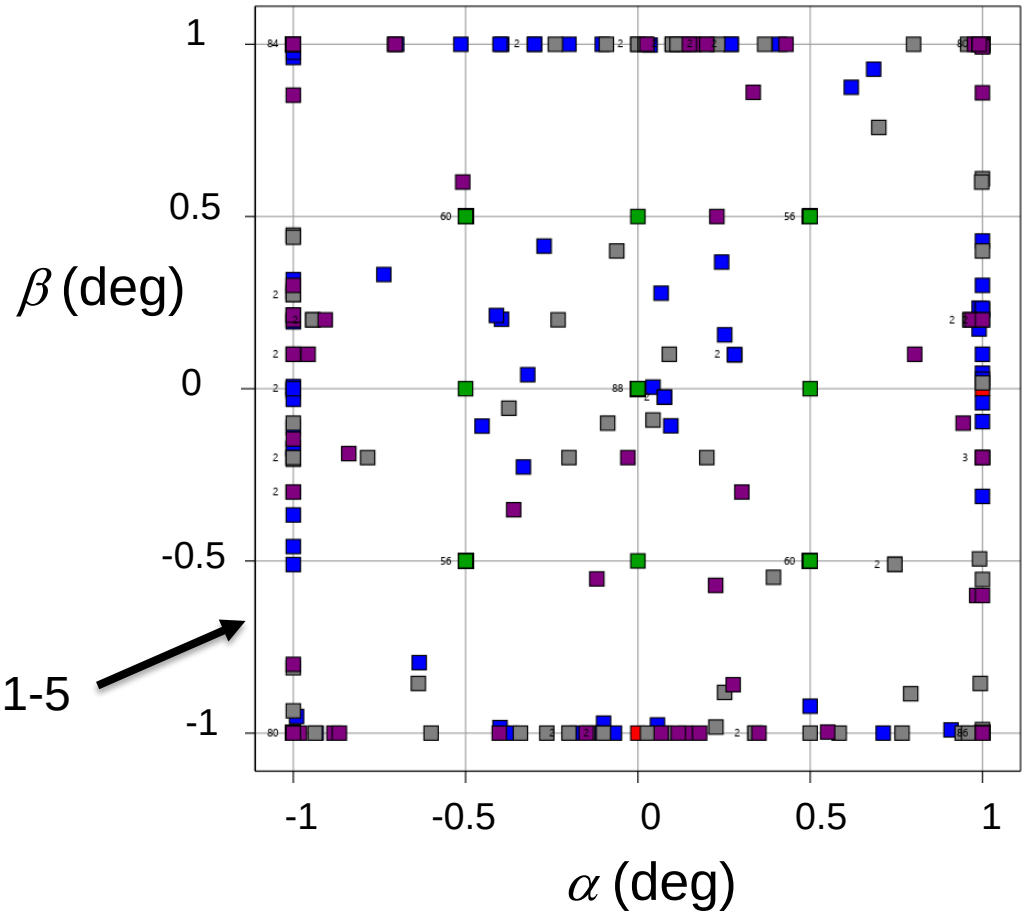


Block Colors
1
2
3
4
5

Blocks 1-2

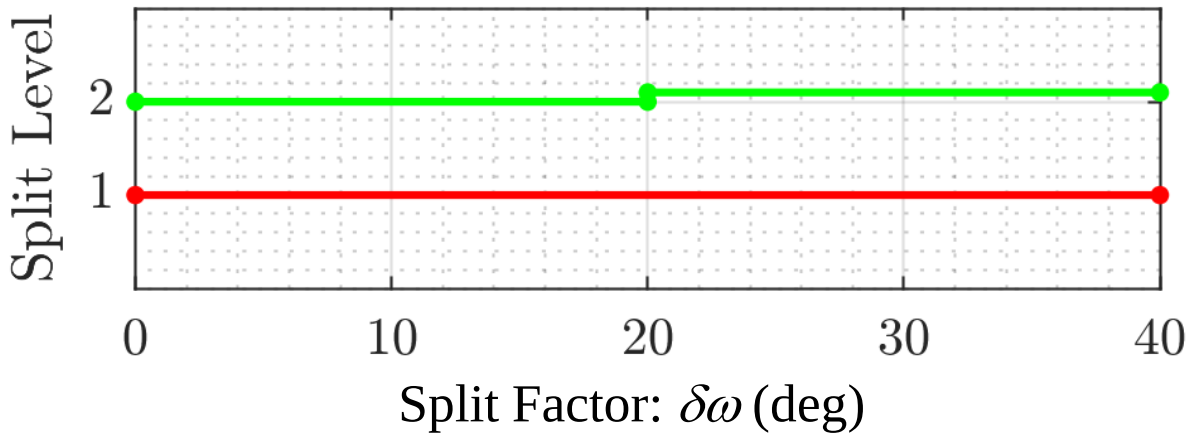
Blocks 1-5

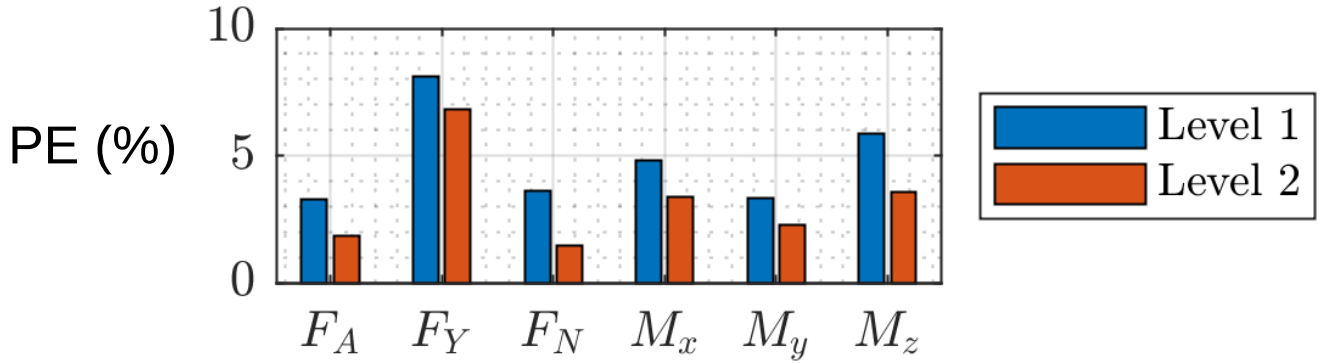
Blocks 3-4 – optimized for minimum PE
Block 5 – validation test data



Splits & PE Metric for LA-8 Study

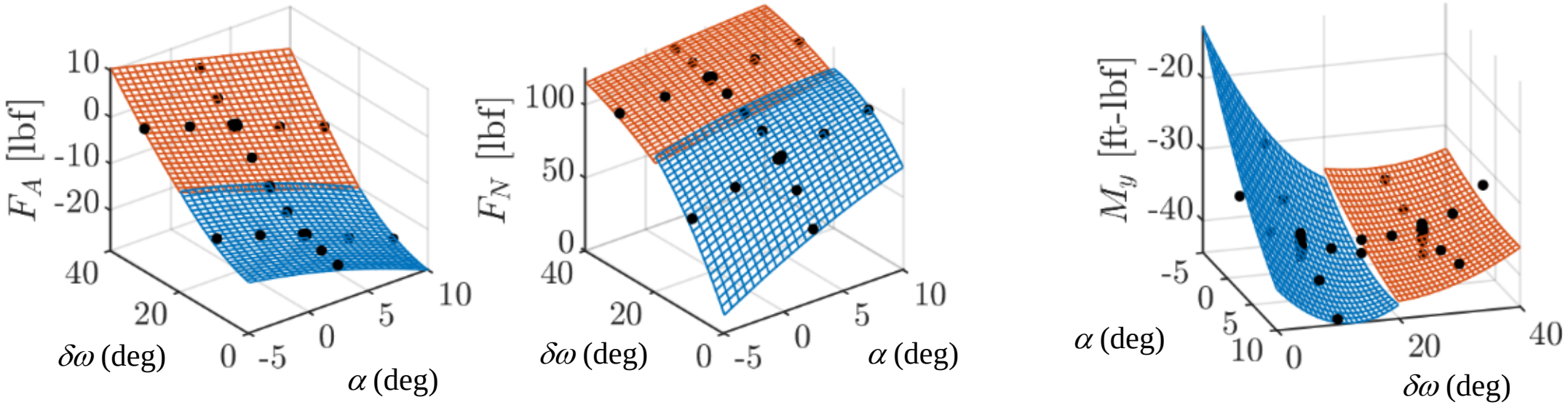
- Test regions are split when models fail prediction goals.
  - Satisfactory model – green bars.
  - Unsatisfactory model – red bars.
- Regions are halved to improve data density & model fidelity.
- In final analysis for LA-8 study, only 1 split required, resulting in 2 separate modeling regions.





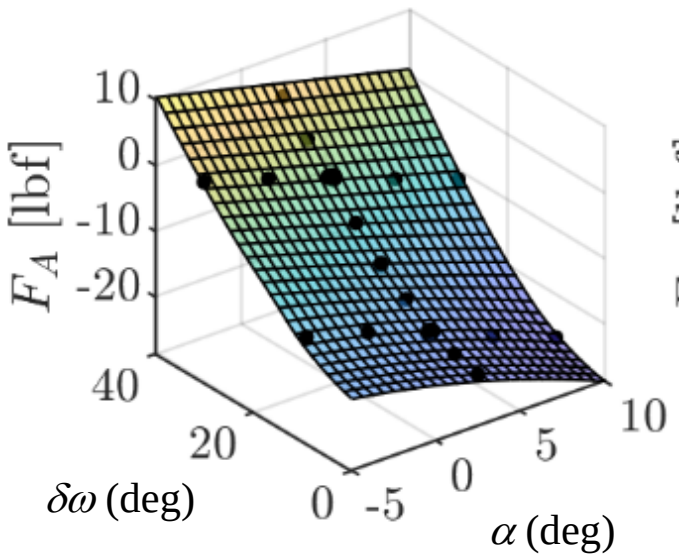
LA-8 Split-Region Models

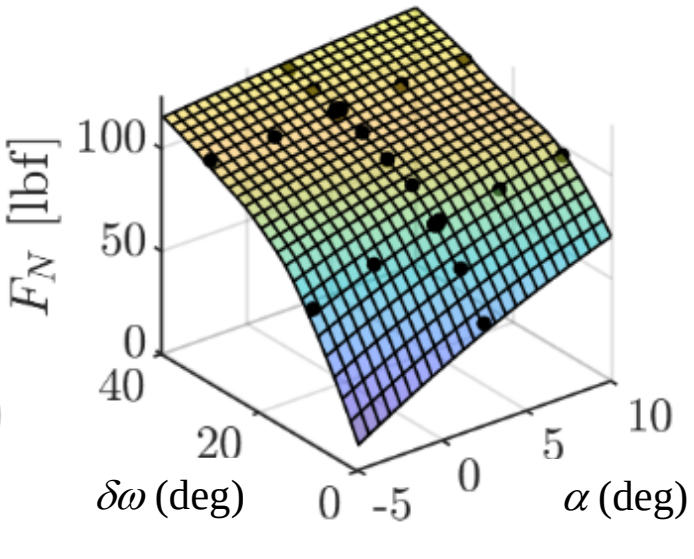
- Longitudinal response models for separate regions as functions of ($\delta\omega$, α).

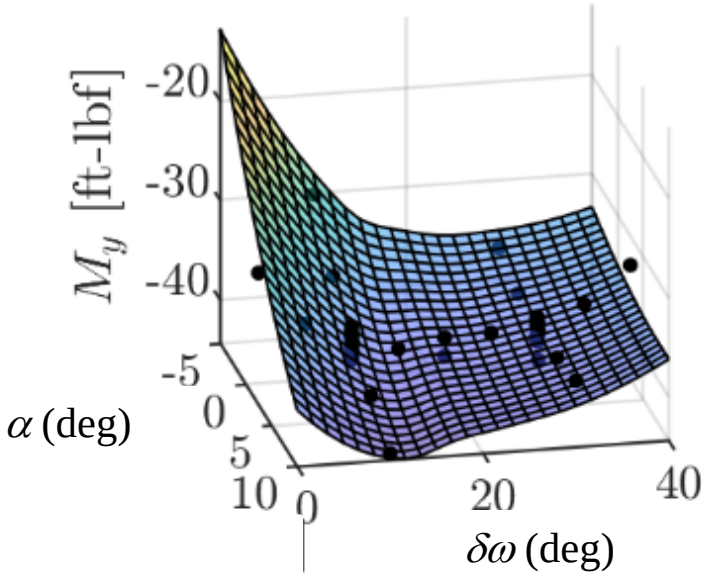


LA-8 Blended Models

- Final global longitudinal response models as functions of ($\delta\omega$, α).







Concluding Remarks

- RAM Motivation – complexity, factor count, interactions, and aero nonlinearities.
- RAM Process – automated, run efficient, and statistically rigorous testing.
- RAM Objective – desired model fidelity with limited data, save time and resources.
- RAM Applications – tunnel (RAM-T) or computational (RAM-C) test environments.
- RAM Demonstration – RAM-T applied to both tunnel and simulated experiments.

Questions

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  - D. B. Hatke, David.B.Hatke@nasa.gov
  - R. C. Busan, Ronald.C.Busan@nasa.gov

- Related papers
  - Murphy, P. C., Simmons, B. M., Hatke, D. B., Busan, R. C., “Rapid Aero Modeling for Urban Air Mobility Aircraft in Computational Tests,” *AIAA SciTech 2021 Forum*, January 2021.
  - Busan, R. C., Murphy, P. C., Hatke, D. B., and Simmons, B. M. “Wind Tunnel Testing Techniques for a Tandem Tilt-Wing, Distributed Electric Propulsion VTOL Aircraft,” *AIAA SciTech Forum*, January 2021.
  - Simmons, B. M., and Murphy, P. C. “Wind Tunnel-Based Aerodynamic Model Identification for a Tilt-Wing, Distributed Electric Propulsion Aircraft,” *AIAA SciTech 2021 Forum*, January 2021.
  - Simmons, B. M. “System Identification for Propellers at High Incidence Angles,” *AIAA SciTech Forum*, January 2021.

- Acknowledgements

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