Engineering Resilient Systems Through the Use of Kestrel a High Fidelity Aircraft Simulation Tool and Compact Efficient Reduced Order Models of the Aircraft Static and Dynamic Loads

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Motivation

• Virtually every new aircraft program encounters unexpected aerodynamic or structural integrity problems
  – Unpredicted complex aerodynamic issues such as vortex/shock/boundary layer interactions have resulted in
    ● issues such as tail buffet, abrupt wing stall, limit cycle oscillations
    ● greatly reduced performance and/or increased structural weight
  – Control surface sizes have been modified on almost every fighter in the modern era
    ● Increased or even decreased empennage after flight demonstrations
  – Modifications after “bending metal” are at the costliest stage in the program and can even kill an aircraft program due to cost and schedule

• Engineering Resilient Systems Requires a More Global View of the System – Unpredicted issues can come from
  – Off design conditions
    ● A few design points analyzed heavily and in between points interpolated
    ● Static aerodynamics analyzed but transient behavior ignored
  – Multi-disciplinary issues
    ● Aerodynamics of rigid bodies dominates analysis with little aero-structural, aero-kinematic/kinetic, or aero-propulsion analysis performed
Motivation

• Why are these off-design and multi-disciplinary issues unchecked?
  – Conceptual/Preliminary Design is the driver of life-cycle cost but has the lowest fidelity information available
  – Empirical methods are fast and successful for on-design conditions but
    ● force designs to remain within knowledge space (conventional)
    ● miss nonlinear aerodynamic issues
  – Low-order aerodynamic tools are fast but
    ● require very highly experienced designers to overcome modeling deficiencies
    ● miss nonlinear aerodynamic issues
  – Loads models are primarily built from a wind tunnel campaign and modified by “fix-ups” over time for configuration changes
    ● Expensive tunnel testing can be delayed significantly from concept to ensure applicability of the data to the detailed design phase
    ● Rarely do a complete re-run for aerodynamic shape changes
    ● Can miss nonlinear aerodynamic issues due to model scale/shape difference from flight configuration
Motivation

To engineer a more resilient system and capture these issues earlier we need high fidelity multi-dimensional tools to be used earlier.

CFD has not been fully incorporated into early conceptual design process due to:
- Cost of a single point calculation
  - May take days on hundreds or even thousands of processors
- Number of single points necessary to fill a database for the flight envelope
  - Can number in the millions of points
  - Do nothing to predict dynamic effects
  - May miss aerodynamic issues between points
- Lack of confidence in whole envelope accuracy (e.g. high alpha, dynamics)
- Simulation traditionally did not incorporate critical systems such as control surfaces, flight control systems, structural models, propulsion effects
- CFD has been used like wind tunnel tests rather than flight tests

We need a new analysis process compatible with the design process that uses the high fidelity tools in a different way.
Motivation

- Proposed revolutionary improvement to the Conceptual/Preliminary Design process to improve resiliency
  - Continue using low-order/empirical methods to reduce number of configurations from order 10,000 to order 10
    - Current methods work well to explore the design space for on-design conditions
    - Result should be an outer mold line (OML) shape for order 10 configurations
  - Use CSE to determine the aerodynamics of the entire envelope
    - Starting with OML quickly build surface and volume meshes (1-2 days)
    - Develop a center of gravity (CG) loads model that incorporates higher order effects (e.g. turbulence, separation, shock/vortex/boundary layer interactions) that can be exercised in milliseconds on a laptop for any point in the envelope and practical maneuver (2-3 days)
    - Develop a surface loads model that can be exercised in milliseconds on a workstation for any point in the envelope and maneuver (same 2-3 days)
    - Explore the CG and surface loads model looking for problem areas and structural design requirements to eliminate late defect discovery
      - Develop database search algorithms looking for strange behavior
    - Optimize configuration for both on- and off-design conditions to make the design more resilient: re-run 2-3 day simulations to regenerate models
  - Use high fidelity CG and surface loads models to size control surfaces, create preliminary structural design, assess mission performance, and create early man-in-the-loop simulator. All from an OML...
Vision for CSE Use in Conceptual/Preliminary Design

After Paring Down to ~10 Design Concepts

Detailed Performance Assessment for the Whole Envelope at High Fidelity Against the RFP

Detailed Engine

Control System Development

Detailed Structural

High Performance Computing

System Identification

Preliminary Control Surface

Preliminary Structural

Preliminary Performance Compared to the RFP Acceptable Yes/No?
Game Changing Combination

High Fidelity CSE Code

- System level high fidelity solver including aerodynamics, structural dynamics, flight mechanics, and propulsion
- Efficient on large processor count (single simulation in hours, full envelope in days)

High Performance Computing

- Large computational resources (order $10^4$ to $10^5$ cores)
- Current US DoD buys are for several machines at approximately 100,000 cores

Compact Model Building

- Approach that can convert days of high fidelity CSE to compact, efficient model for use on laptop/workstation
- Approach that can allow higher and higher fidelity simulation (add control surfaces, aeroelasticity, propulsion, etc.)
Compact Model Approach (CG Loads)

- Simulate closed-loop, full-scale a/c at edge-of-the-envelope conditions with a single, complex and efficient maneuver (possibly non-flyable) per flight condition

- Generate nonlinear, dynamic reduced-order aerodynamic models

\[
C_L(\alpha, \beta, p, q, r) = C_1 + C_2\alpha + C_3q + C_4p^2 + C_5\alpha q^2 + C_6\beta pq +
\]

\[
+ C_7\beta p + C_8\alpha^2 q + C_9r + C_{10}\alpha \beta^2 + C_{11}\alpha^3 + C_{12}pr +
\]

\[
+ C_{13}\beta^2 p + C_{14}\beta q + C_{15}p + C_{16}\beta^2
\]

- Use model for S&C analysis, flight simulation, control system design, etc.
  - New approach much more efficient than traditional “brute force” static solutions filling a database and then computing derivatives numerically
  - Allows Engineers flexibility to handle any new configuration and independence from contractors
Aircraft System Identification (SID)

- SID – construct a mathematical model of a system
- SID goal: determine the functional dependence b/w input and output
- Already applied to WT and FT data for:
  - Flight simulation
  - Control system design
  - Dynamic analysis
- Our approach: apply SID to CFD data
  - Obtain both Static and Dynamic data from single computational maneuver
- Two methods: MVP and RBF

\[
\begin{align*}
\text{INPUT} & \quad \alpha, \beta, \ldots \\
\text{MVP} & \quad \begin{cases}
  f(\alpha, \beta, \ldots) = \\
  g(\alpha, \beta, \ldots) = \\
  \vdots
\end{cases} \\
\text{RBF} & \quad \text{Artificial Neural Network} \\
\text{OUTPUT} & \quad f, g, \ldots
\end{align*}
\]
Compact Model Approach (cont.)

1) Model Training
   - Training input signal (non-flyable)
     - $\alpha(t), \beta(t), ...$

2) Model Validation
   - Validation input signal (dissimilar, flyable/non-flyable)
     - $\alpha(t), \beta(t), ...$

3) Model Prediction
   - Flight-test maneuver (flyable)

   - Nonlinear dynamic aero model
   - $C_L, C_m, ...$
   - Safe?
     - yes
     - Limit envelope
     - $C_L, C_m, ...$

   - CSE Code
   - SYSID Tool
     - kSID, kPOD
   - $C_L, C_m, ...$
   - compare

   - EXP
   - CSE Code
   - $C_L, C_m, ...$
   - compare
CSE Code (Kestrel) Architecture

- Unique Event Driven Infrastructure with Modular Components
- Unstructured Navier-Stokes CFD Solver (kAVUS)
  - Cell Centered, Finite Volume, 2nd Order Temporal and Spatial Solver
  - Hybrid Mesh – Tetrahedrals, Prisms, Pyramids, Hexahedrals
  - Euler, Laminar, and Turbulent Flow (SA, SST, SA-DDES, SST-DES)
  - Moving Mesh, Deforming Mesh Capable with GCL
- Rigid/Aeroelastic Prescribed and 6DOF Predictive Motion Capable
- UI for pre-processing pre-flight capability to build complex motions
- UI for post-processing SYSID model building and data analysis

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Baseline Aerodynamic CG Loads Modeling Using System Identification
AGARD 445.6 Wing Simulations

- **Half-span grid with:**
  - 2,974,944 cells
  - 2,101,020 prisms
  - 848,184 tets

- **Flow conditions:**
  - $M_{\infty}=0.95$, $P_{\infty}=0.66$ lb/in$^2$, $T_{\infty}=464.2$R

- **Numerical parameters:**
  - $\Delta t=0.0002s$
  - 5 Newton sub-iterations
  - SA-DDES

- **Sinusoidal Pitch Chirp Training Maneuver**
  - $\alpha = 0 \pm 10$ deg, frequency varying from 0.2 to 20 cycles/sec

- **Used System Identification to “fit” the data**

\[
C_L(\alpha, q, \dot{q}) = C_1 + C_2 + C_3 q + C_4 q^3 + C_5 q\dot{q} + C_6 q + \]
\[
C_7 q^2 + C_8 q^3 + C_9 q^2 + C_{10} q^2 \dot{q} + C_{11} \dot{q}^3 + C_{12} \dot{q} + \]
\[
C_{13} \dot{q} + C_{14} q + C_{15} q + C_{16} q^2 + C_{17} \dot{q}^2 + C_{18} \dot{q} + \]
\[
C_D(\alpha, q, \dot{q}) = C_1 + C_2 q + C_3 q + C_4 q^2 + C_5 q\dot{q} + C_6 q^2 + \]
\[
C_7 q + C_8 q^3 + C_9 q + C_{10} q^2 + C_{11} \dot{q} + C_{12} q^2 \dot{q} + \]
\[
C_{13} q^2 + C_{14} q + C_{15} \dot{q}^3 + C_{16} q^3 + C_{17} \dot{q}^2 + \]
\[
C_M(\alpha, q, \dot{q}) = C_1 + C_2 + C_3 q + C_4 q^3 + C_5 q\dot{q} + C_6 q\dot{q}^2 + \]
\[
C_7 q^2 + C_8 q^3 + C_9 q^2 \dot{q} + C_{10} \dot{q} + C_{11} \dot{q}^3 + C_{12} \dot{q}^2 + \]
\[
C_{13} \dot{q} + C_{14} q^2 + C_{15} \dot{q}^2 + C_{16} q + C_{17} q^2 + C_{18} \dot{q} + \]
Sinusoidal Pitch Chirp Training Maneuver
Sinusoidal Pitch Chirp Training Maneuver

- Comparison of System Identification Generated Model from the Training Maneuver with CFD Static Solutions
Complex Configuration Aerodynamic CG Loads Modeling Using System Identification
F-16C Static SID Analysis
Lockheed Performance Data vs. SYSID (Kestrel)

- Composite Pitch-Roll-Yaw Chirp
  - \( \alpha = 0-25 \) deg, \( \beta = 0\pm2 \) deg, \( \dot{\phi} = 0\pm70 \) deg/sec
  - Multiple rotations

- Input signals orthogonal

- Requires full span F-16C grid

- Conditions: \( M=0.6 \)

- Compare against Lockheed Martin Flight Test & Performance Data
  - LM: tip AIM-9s; CFD/SID: tip LAU-129s
F-16C Static SID Analysis
Lockheed Performance Data vs. SYSID (Kestrel)

- **Composite Pitch-Roll-Yaw Chirp**
  - $\alpha = 0$-25 deg, $\beta = 0 \pm 2$ deg, $\dot{\phi} = 0 \pm 70$ deg/sec
  - Multiple rotations

- **Input signals orthogonal**

- **Requires full span F-16C grid**

- **Conditions:** $M=0.6$

- **Compare against Lockheed Martin Flight Test & Performance Data**
  - LM: tip AIM-9s; CFD/SID: tip LAU-129s
Extension to Surface Loads Modeling Using Proper Orthogonal Decomposition (POD) and System Identification
Modified Approach for Surface Loads Model Development

- Perform a training maneuver similar to the CG loads method and collect loads (pressure or forces) at each surface mesh location as a function of time.

- Perform a Proper Orthogonal Decomposition (POD) of the surface loads to determine a set of aero surface modes and companion POD coefficients as a function of time.

- Perform a System Identification analysis of the maneuver inputs ($\alpha$, $\beta$, $\phi$, $P$, $Q$, $R$, ...) and POD coefficient outputs to determine a functional form of the POD coefficients.

- Resulting model is predictive, compact, efficient, accurate on and off-design, and easy to re-generate with new configurations.

- Things to work on...
  - Need for improvement in training maneuvers designed for surface load generation.
  - System Identification methods for fitting the POD coefficients.
Loads Model Development
Example: AGARD 445.6, M=0.95

- Simulated a pitch sinusoidal chirp
  - Initial/final frequencies of 0.2/10 cycles per second
  - Initial/final amplitude of 10/5 degrees

- POD of the training maneuver developed with 20 modes

- System Identification used to “fit” data
  - Multi-variate polynomial approach proved inadequate for POD coefficients (not an exhaustive study)
  - Neural network approach proved fruitful

- Compared POD/SYSID prediction with CSE for a sinusoidal pitch with 10 deg amplitude and 2 cycles/sec frequency
AGARD 445.6 Wing
Comparison of Surface Pressure for CSE to POD/SYSID
2 Cycles/Sec Pitch Maneuver
AGARD 445.6 Wing

Comparison of Surface Pressure for CSE to POD/SYSID
2 Cycles/Sec Pitch Maneuver

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2 Cycles/Sec Pitch Maneuver

![Graph showing comparison of CSE Pressure to POD/SYSID Pressure with color scale ranging from 0.25 to 0.85]
AGARD 445.6 Wing
Comparison of Surface Pressure for CSE to POD/SYSID
2 Cycles/Sec Pitch Maneuver
AGARD 445.6 Wing
Comparison of Surface Pressure for CSE to POD/SYSID
2 Cycles/Sec Pitch Maneuver
AGARD 445.6 Wing
Comparison of Surface Pressure for CSE to POD/SYSID
2 Cycles/Sec Pitch Maneuver

PRESSURE
CSE Pressure
POD/SYSID Pressure

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AGARD 445.6 Wing
Comparison of Surface Pressure for CSE to POD/SYSID
2 Cycles/Sec Pitch Maneuver

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AGARD 445.6 Wing
Comparison of Surface Pressure for CSE to POD/SYSID
2 Cycles/Sec Pitch Maneuver
AGARD 445.6 Wing
Comparison of Surface Pressure for CSE to POD/SYSID 2 Cycles/Sec Pitch Maneuver

![Graph showing comparison of CSE and POD/SYSID surface pressures with time]
AGARD 445.6 Wing
Comparison of Surface Pressure for CSE to POD/SYSID
2 Cycles/Sec Pitch Maneuver
AGARD 445.6 Wing
Comparison of Surface Pressure for CSE to POD/SYSID
2 Cycles/Sec Pitch Maneuver
AGARD 445.6 Wing
Comparison of Surface Pressure for CSE to POD/SYSID
2 Cycles/Sec Pitch Maneuver

- Started with only an OML
- Built a POD of a training maneuver
- Built a predictive SYSID of the POD
- Re-constructed a maneuver using the predictive SYSID/POD
- Compared well with CSE
Ultimate Goal

- Integrate all modules into high-fidelity tool capable of developing accurate models of full elastic aircraft configurations

\[ \text{Loads} = f(\bar{q}, M, \quad, \quad, q, \quad, q^2, \quad ) \]
Conclusions & Outlook

- Deficiencies in the current conceptual, preliminary, and detailed design process have been noted.

- A new method has been proposed to address these deficiencies using CSE early in the design phase using:
  - A system level high-fidelity CSE tool
  - High performance computing
  - Compact efficient models built from high-fidelity CSE

- Examples have been given of the method applied to CG loads and surface loads of a wing showing great promise for the method on realistic configurations.

- Future work incorporating control surfaces, aeroelasticity, automatic flight control systems, and propulsion has been proposed.
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Questions?
F-16 Aerodynamic CG Loads Modeling Using System Identification
Baseline F-16 Simulations

- **Half-span grid with:**
  - 790,109 nodes
  - 3,171,892 cells
  - 8 prismatic layers

- **Generated with NASA tool VGRIDns**

- **Cells concentrated in the strake vortex**

- **Forebody bump, diverter, ventral fin modeled**

- **Corrected engine mass flow modeled**

- **Flow conditions:**
  - $M_{\infty}=0.25, 0.6, .8, .9, .95, 1.2, 1.6, 2.0$
  - Altitudes = 5k, 10k, 20k, 30k

- **Numerical parameters:**
  - $\Delta t=0.0002s$
  - 3 Newton sub-iterations
  - DDES based on SA with RC
Multi-axis Training Maneuver
Pitch-Yaw Chirp

- Composite Pitch-Yaw Chirp maneuver allows a single motion input to create a model including motion about two axes
  - $\alpha = 15\pm15\,\text{deg}$, $\beta = 0\pm15\,\text{deg}$
- Input signals made orthogonal (dot product = 0)
- Requires full span F-16C grid
- Conditions: $M=0.6$, Alt.=5k ft.

\[ \text{Graphs showing flight data and grid layout.} \]
System ID Applied to Multi-axis Training Maneuver: Pitch-Yaw Chirp

- **SIDPAC Model:**

  \[ C_L(\alpha, \beta, p, q, r) = C_1 + C_2\alpha + C_3q + C_4p^2 + C_5\alpha q + C_6\beta pq \]

  \[ + C_7\beta p + C_8\alpha^2 q + C_9r + C_{10}\alpha \beta^2 + C_{11}\alpha^3 + C_{12}pr + \]

  \[ + C_{13}\beta^2 p + C_{14}\beta^2 q + C_{15}p + C_{16}\beta^2 \]

- **Validated against static \( C_L-\alpha \) data and single axis motion pitch chirp**
2.5g Wind Up Turn Flight Test Maneuver

- Prescribed motion based on flight test data (rotations only)
- Use reduced order loads model to perform maneuver & compare
- Good Lift prediction
- Drag prediction not as good as expected
- Conditions: M=0.6, Alt.=5k ft.

![Lift and Drag Plots](image-url)
Training Maneuvers in 6-DoF

- Incorporate both translation and rotation into the training maneuver to provide better regressor space coverage
- Much better drag model predictions resulted