Dynamic Flight Simulation (DFS) for MAD/MUTT

Erich Ritz and P. C. Chen

ZONA TECHNOLOGY INC

Presented at ASE Workshop, NASA Langley, VA on April 18-19, 2012

9489 E. Ironwood Square Drive, Scottsdale, AZ 85258, Tel. (480) 945-9988, Fax (480) 945-6588, E-mail: info@zonatech.com

Why DFS?

- Flight dynamics model solves the nonlinear 6 DoF equations of motion with an aerodynamic database to assess the stability, performance and handling quality of the aircraft.
  - The aerodynamic database is usually generated by wind tunnel testing on a rigid aircraft.
  - At best, the nonlinear aerodynamic database can be "flexiblized" using a quasi-static correction factor to account for the static aeroelastic effects.
  - Inclusion of dynamic aeroelastic effects are difficult and, thereby, usually ignored.

- Dynamic aeroelastic model combines the structural dynamics and unsteady aerodynamics to predict the static and dynamic aeroelastic response.
  - The equations of motion, at least for the structural dynamics, are usually linear.
  - The predicted rigid body aerodynamics by the unsteady aerodynamic methods may not agree with the wind tunnel data.

- Flight control law based in the 6 DoF rigid aircraft model is inadequate to handle the slender, more flexible and/or sizable aircraft. Therefore, aeroelastic effects must be considered during the flying quality evaluation of aircraft.
  - Helios mishap in June 2003 possibly due to an interaction between aeroelastic deformation and longitudinal stability.
  - A sensor-craft wind tunnel model encountered unexpected fore-aft oscillation in the TDT.

Objectives

- Develop a linear Dynamic Flight Simulation (DFS) tool for MAD/MUTT
  - Combining the flight dynamics and aeroelastic models in a Simulink environment.
  - Capable of simulating the key aeroelastic coupling mechanisms between structural and unsteady aerodynamic effects with classical rigid-body dynamics.
- DFS should be formulated in principle by using commonly agreed terms from flight dynamics and aeroelasticity.
  - Leave the flight dynamic model with least change so that DFS remains in the framework of 6 DoF simulation.
  - When the aeroelastic effects are removed, DFS reduces to the flight dynamic model.
- DFS can be used for:
  - Control law development.
  - Maneuvering flight simulation.
  - Handling quality assessment.

The Approach

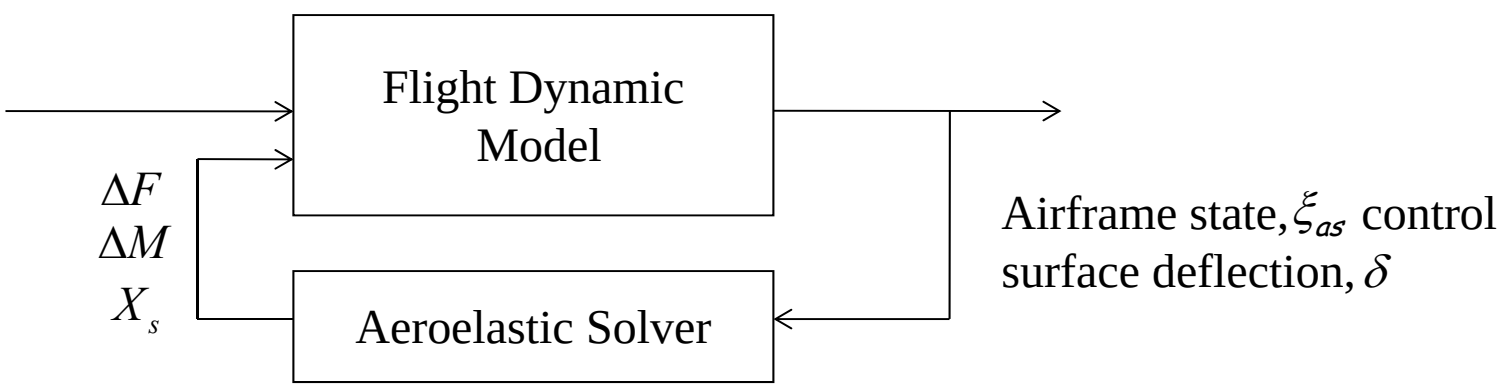
- Incorporates the add-on incremental forces and moments, ΔF and ΔM, due to aeroelastic effects in the nonlinear flight simulation model.

$$m\left[\dot{V}_b + \Omega_b \times V_b - T_{be} g_e\right] = F_{ext} + \Delta F$$

$$I_b \dot{\Omega}_b + \Omega_b \times I_b \Omega_b = M_{ext} + \Delta M$$

- Adds the structural oscillation, X_s, at the sensor locations to the sensor reading of rigid body motion.

- Modifies the linear aeroelastic equations of motion as an aeroelastic solver to provide $\Delta F, \Delta M$, and X_s at each time step in the nonlinear flight simulation model.



Time-Domain Aeroservoelastic Equations of Motion (I)

- The frequency-domain (k) Generalized Aerodynamics Forces (GAF) are transformed to the time domain via the Rational Function Approximation (RFA).

$$\left[Q_{hh}(k), Q_{hc}(k)\right] = \left[A_{hh_0}, A_{hc_0}\right] + \frac{L}{V}\left[A_{hh_1}, A_{hc_1}\right]s + \left(\frac{L}{V}\right)^2\left[A_{hh_2}, A_{hc_2}\right]s^2 + \left[D\right]\left\{x_a\right\}$$

where $\left\{x_a\right\} = \left[\left[I\right]S - \frac{V}{L}\left[R\right]\right]^{-1}\left[E_h, E_c\right]S$ is the aerodynamic lag states.

- Two methods for RFA are available in the ZAERO ASE module
  - The Minimum State Method
  - The Roger's Method

- Combining the time-domain RFA with the structural equation yields:

$$\left[M_{hh}\right]\left\{\ddot{\xi}\right\} + \left[C_{hh}\right]\left\{\dot{\xi}\right\} + \left[K_{hh}\right]\left\{\xi\right\} + \left[M_{hc}\right]\left\{\ddot{\delta}\right\}$$
$$= q_\infty\left[\left[A_{hh_0}\right]\left\{\xi\right\} + \frac{L}{V}\left[A_{hh_1}\right]\left\{\dot{\xi}\right\} + \frac{L^2}{V^2}\left[A_{hh_2}\right]\left\{\ddot{\xi}\right\}\right]$$
$$+ q_\infty\left[\left[A_{hc_0}\right]\left\{\delta\right\} + \frac{L}{V}\left[A_{hc_1}\right]\left\{\dot{\delta}\right\} + \frac{L^2}{V^2}\left[A_{hc_2}\right]\left\{\ddot{\delta}\right\}\right] + q_\infty\left[D\right]\left\{x_a\right\}$$

Time-Domain Aeroservoelastic Equations of Motion (II)

- Defining an aeroelastic state vector as

$$\{X_{ae}\} = \{\xi, \dot{\xi}, X_a\}^T$$

- The ASE state-space equations are formulated:

$$\{\dot{X}_{ae}\} = [A_{ae}]\{X_{ae}\} + [B_{ae}]\{U_{ae}\}$$

where

$$\{U_{ae}\} = \{\delta, \dot{\delta}, \ddot{\delta}\}^T$$

$$[A_{ae}] = \begin{bmatrix} [0] & [I] & [0] \\ -[\bar{M}]^{-1}\left[[K_{hh}] - q_\infty [A_{hh_0}]\right] & -[\bar{M}]^{-1}\left[[C_{hh}] - q_\infty \frac{L}{V}[A_{hh_1}]\right] & q_\infty [\bar{M}]^{-1}[D] \\ [0] & [E_h] & \frac{V}{L}[R] \end{bmatrix}$$

$$[B_{ae}] = \begin{bmatrix} [0] & [0] & [0] \\ q_\infty [\bar{M}]^{-1}[A_{hc_0}] & q_\infty \frac{L}{V}[\bar{M}]^{-1}[A_{hc_1}] & -[\bar{M}]^{-1}\left[[M_{hc}] - \frac{q_\infty L^2}{V^2}[A_{hc_2}]\right] \\ [0] & [E_c] & [0] \end{bmatrix}$$

and

$$[\bar{M}] = \left[[M_{hh}] - \frac{q_\infty L^2}{V^2}[A_{hh_2}]\right]$$

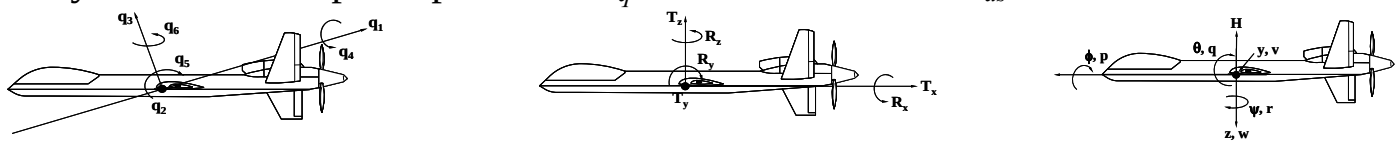
- The number of states is $2 \times N_h + N_{lag}$ if the Minimum State Method is used and is $2 \times N_h + N_h \times N_{lag}$ if the Roger's Method is used.

Technical Issues Involved in the Development of Aeroelastic Solver

- Rigid body modes of the linear aeroelastic equations of motion are usually computed by the finite element analysis and defined in the principle axis.
  - To be consistent with the flight dynamic model, they must be transformed to the airframe states such as $\alpha, \beta, p, q, \gamma,$ …etc.
  - The generalized mass matrix of the rigid body modes, usually a diagonal matrix, needs to be converted to the rigid body mass matrix that involves the inertial cross products such as I_{xz} , I_{yz}, …, etc.
- The rigid-body aerodynamics computed by the unsteady aerodynamic methods should be replaced by the wind tunnel data.
- Gravity should be in the aeroelastic solver.
  - The linear aeroelastic equations of motion lacks the gravity term.
  - Without the gravity term, phugoid mode can not be accurately recovered by the aeroelastic solver.
- If the flight dynamic model is already incorporated with static aeroelastic effects, these effects must be excluded from aeroelastic solver.

Transformation of Rigid-Body Modes to Airframe States

- Based on the work by Baldelli, Chen, and Panza (Baldelli, Chen, Panza, Journal of Aircraft, Vol. 43, No. 3, May-June 2006) a transformation matrix [T_A] can be formulated that transforms the rigid-body modes in the principle axis η_q to airframe status ξ_{as}.



(a) Generalized Coordinates of Rigid Body d.o.f. in FEM Analysis (Principal Axis)

(b) Rigid Body d.o.f. in Body Axis:

(c) Airframe States:

$$\{\eta_q\}^T = \{q_1, q_2, \ldots q_6\} \qquad \{\eta_r\}^T = \{T_x, T_y, T_x, R_x, R_y, R_z\} \qquad \{\xi_{as}\}^T = \{a, \beta, p, q, r, \phi, \theta, \psi, \ldots\}$$

$$\{\eta_q\} = [R_p]^{-1}[R_B]\{\eta_r\} \qquad \begin{Bmatrix} \eta_r \\ \dot{\eta}_r \end{Bmatrix} = [T_A]\{\xi_{as}\}$$

For Symmetric Maneuvers [T_A] is defined as:

$$\begin{Bmatrix} T_x \\ T_z \\ R_y \\ \dot{T}_x \\ \dot{T}_z \\ \dot{R}_y \end{Bmatrix} = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -V_\infty & V_\infty & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} x \\ u \\ h \\ \alpha \\ \theta \\ q \end{Bmatrix}$$

For Anti-Symmetric Maneuvers [T_A] is defined as:

$$\begin{Bmatrix} T_y \\ R_x \\ R_z \\ \dot{T}_y \\ \dot{R}_x \\ \dot{R}_z \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & V_\infty & 0 & 0 & 0 & V_\infty \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \end{bmatrix} \begin{Bmatrix} y \\ \beta \\ p \\ r \\ \phi \\ \psi \end{Bmatrix}$$

Conversion of Generalized Mass Matrix to Rigid-Body Mass Matrix

- The transformation matrix from principle axis to body axis can convert the rigid-body sub-matrix in the generalized mass matrix to rigid-body mass matrix and leave the elastic generalized mass matrix unchanged.

$$[M] = \left[\begin{array}{c|c} M_{rb} & 0 \\ \hline 0 & M_{ee} \end{array}\right]$$

where matrices $[M_{rb}]$ and $[M_{ee}]$ are defined as,

$$[M_{rb}] = \begin{bmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & 0 & 0 & I_{xx} & 0 & I_{xz} \\ 0 & 0 & 0 & 0 & I_{yy} & 0 \\ 0 & 0 & 0 & I_{xz} & 0 & I_{zz} \end{bmatrix}, \qquad [M_{ee}] = \begin{bmatrix} \ddots & & & & \\ & \ddots & & & \\ & & m_{ii} & & \\ & & & \ddots & \\ & & & & \ddots \end{bmatrix}$$

m is the total mass of the aircraft. I_{xx}, I_{xy}, and I_{zz}, are the mass moment of inertial of the aircraft.

Replacement of the Rigid Body Aerodynamics by Wing Tunnel Data (I)

- The rigid body sub-matrices in the rational function approximation matrices can be replaced by the wind-tunnel measured aerodynamic stability derivatives.

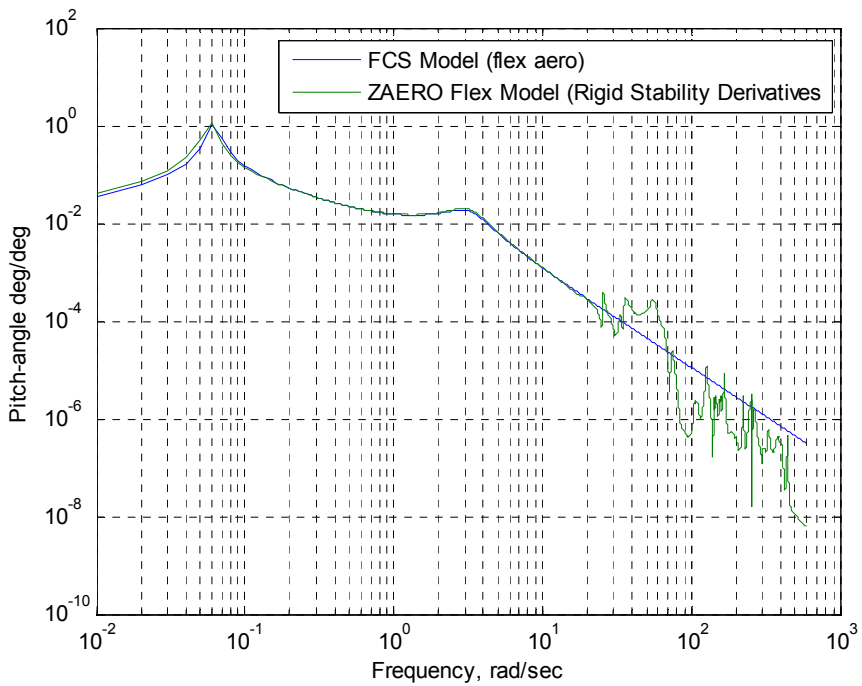
$$
\left[A_0\right] = \begin{bmatrix}
0 & 0 & 0 & 0 & -S\left(C_{D_\alpha} - C_{L_o}\right) - \frac{mg}{q_\infty}\cos\theta_o & -SC_{D_\beta} \\
0 & 0 & 0 & \frac{mg}{q_\infty}\cos\phi_o & -SC_{y_\alpha} & -SC_{y_\beta} \\
0 & 0 & 0 & 0 & -S\left(C_{L_\alpha} + C_{D_o}\right) & -SC_{L_\beta} \\
0 & 0 & 0 & 0 & -SbC_{l_\alpha} & -SbC_{l_\beta} \\
0 & 0 & 0 & 0 & -ScC_{m_\alpha} & -ScC_{m_\beta} \\
0 & 0 & 0 & 0 & -SbC_{n_\alpha} & -SbC_{n_\beta}
\end{bmatrix}_{6x6}
$$

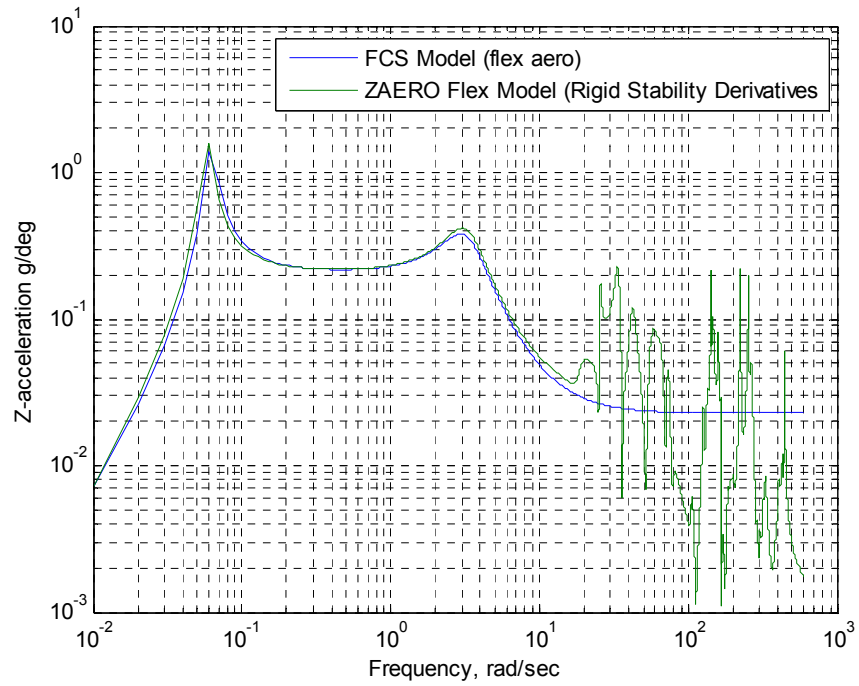
$$
\left[A_1\right] = \begin{bmatrix}
\frac{2S\left(C_{D_u} + C_{D_o}\right)}{\left(c/2\right)} & \frac{-SC_{D_\beta}}{\left(c/2\right)} & \frac{S\left(C_{D_\alpha} - C_{L_o}\right)}{\left(c/2\right)} & \frac{-0.5SbC_{D_p}}{\left(c/2\right)} & \frac{-0.5Sc\left(C_{D_{\dot\alpha}} + C_{D_q}\right)}{\left(c/2\right)} & \frac{-0.5Sb\left(C_{D_{\dot\beta}} + C_{D_r}\right)}{\left(c/2\right)} \\
\frac{2S\left(C_{y_u} + C_{y_o}\right)}{\left(c/2\right)} & \frac{-SC_{y_\beta}}{\left(c/2\right)} & \frac{SC_{y_\alpha}}{\left(c/2\right)} & \frac{-0.5SbC_{y_p}}{\left(c/2\right)} & \frac{-0.5Sc\left(C_{y_{\dot\alpha}} + C_{y_q}\right)}{\left(c/2\right)} & \frac{-0.5Sb}{\left(c/2\right)}\left(C_{y_{\dot\beta}} + C_{y_r}\right) \\
\frac{2S\left(C_{L_u} + C_{L_o}\right)}{\left(c/2\right)} & \frac{-SC_{L_\beta}}{\left(c/2\right)} & \frac{S\left(C_{L_\alpha} + C_{D_o}\right)}{\left(c/2\right)} & \frac{-0.5SbC_{L_p}}{\left(c/2\right)} & \frac{-0.5Sc\left(C_{L_{\dot\alpha}} + C_{L_q}\right)}{\left(c/2\right)} & \frac{-0.5Sb\left(C_{L_{\dot\beta}} + C_{L_r}\right)}{\left(c/2\right)} \\
\frac{2SbC_{l_u}}{\left(c/2\right)} & \frac{-SbC_{l_\beta}}{\left(c/2\right)} & \frac{SbcC_{l_\alpha}}{\left(c/2\right)} & \frac{-0.5Sb^2C_{l_p}}{\left(c/2\right)} & \frac{-0.5Sbc\left(C_{l_{\dot\alpha}} + C_{l_q}\right)}{\left(c/2\right)} & \frac{-0.5Sb^2}{\left(c/2\right)}\left(C_{l_{\dot\beta}} + C_{l_r}\right) \\
\frac{2Sc\left(C_{m_u} + C_{m_o}\right)}{\left(c/2\right)} & \frac{-ScC_{m_\beta}}{\left(c/2\right)} & \frac{ScC_{m_\alpha}}{\left(c/2\right)} & \frac{-0.5SbcC_{m_p}}{\left(c/2\right)} & \frac{-0.5Sc^2\left(C_{m_{\dot\alpha}} + C_{m_q}\right)}{\left(c/2\right)} & \frac{-0.5Sbc\left(C_{m_{\dot\beta}} + C_{m_r}\right)}{\left(c/2\right)} \\
\frac{2SbC_{n_u}}{\left(c/2\right)} & \frac{-SbC_{n_\beta}}{\left(c/2\right)} & \frac{SbC_{n_\alpha}}{\left(c/2\right)} & \frac{-0.5Sb^2C_{n_p}}{\left(c/2\right)} & \frac{-0.5Sbc\left(C_{n_{\dot\alpha}} + C_{n_q}\right)}{\left(c/2\right)} & \frac{-0.5Sb^2}{\left(c/2\right)}\left(C_{n_{\dot\beta}} + C_{n_r}\right)
\end{bmatrix}_{6x6}
$$

- A gravity term mg is added into the $[A_0]$ matrix.

Replacement of the Rigid Body Aerodynamics by Wing Tunnel Data (II)

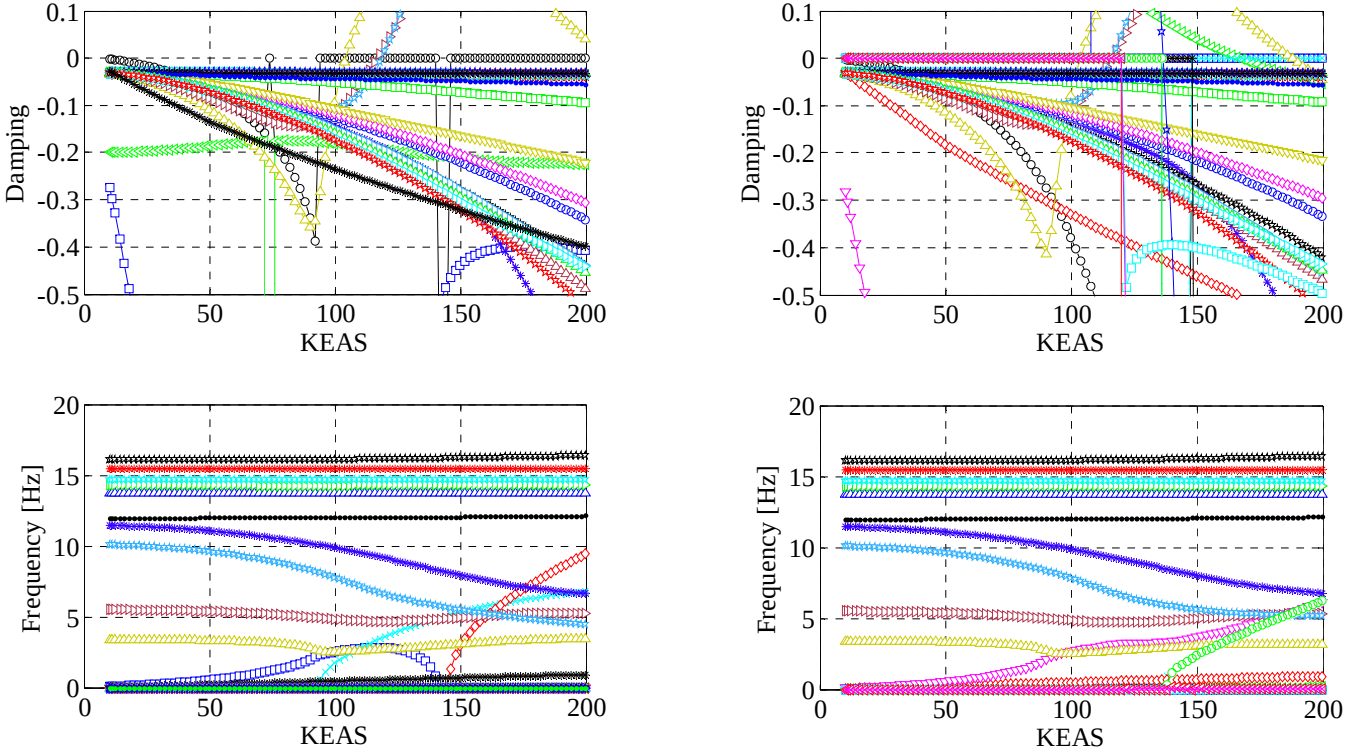
- Good match with the Flight Dynamic results.





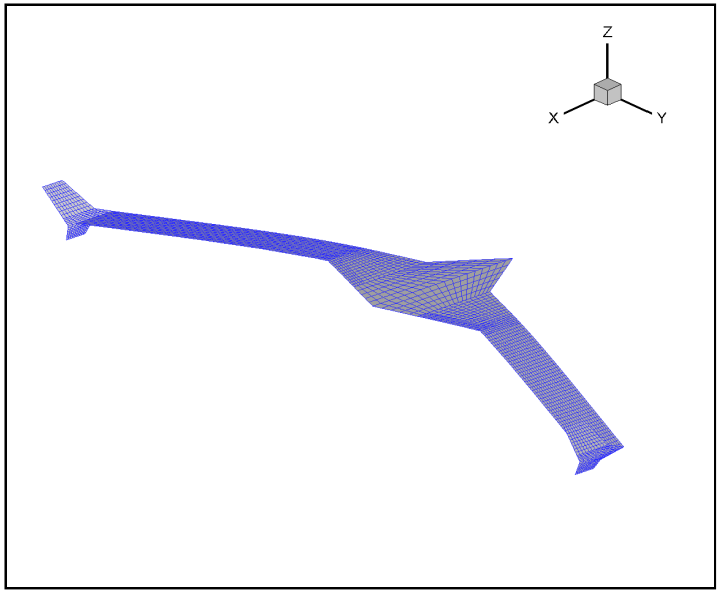
Validation of the ASE State-Space Equation for MAD/MUTT at Empty Fuel Condition

- The Minimum State Method with six aerodynamic lag states are used.
- 6 rigid bodies and 24 elastic modes are included.

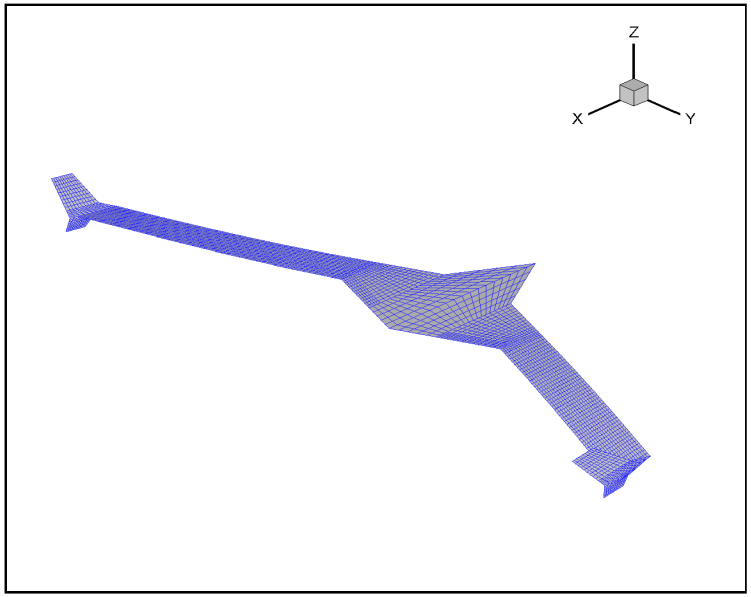


Flexible Empty Flutter Mode	ASE		g-method	
	V_f (KEAS)	ω_f (Hz)	V_f (KEAS)	ω_f (Hz)
BFF	104.4	2.58	103.8	2.56
AWBT	116.9	4.70	116.0	4.73
SWBT	118.7	6.66	116.3	6.82

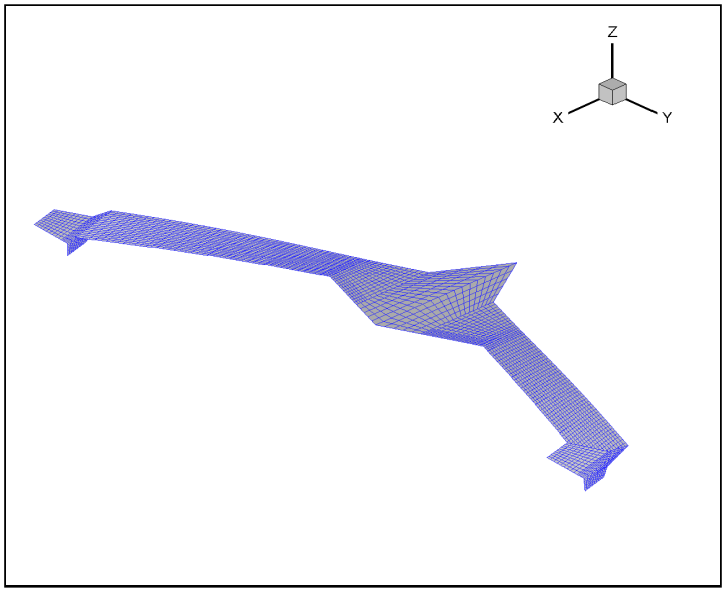
Flutter Modes of the Empty Fuel Condition



BFF Mode

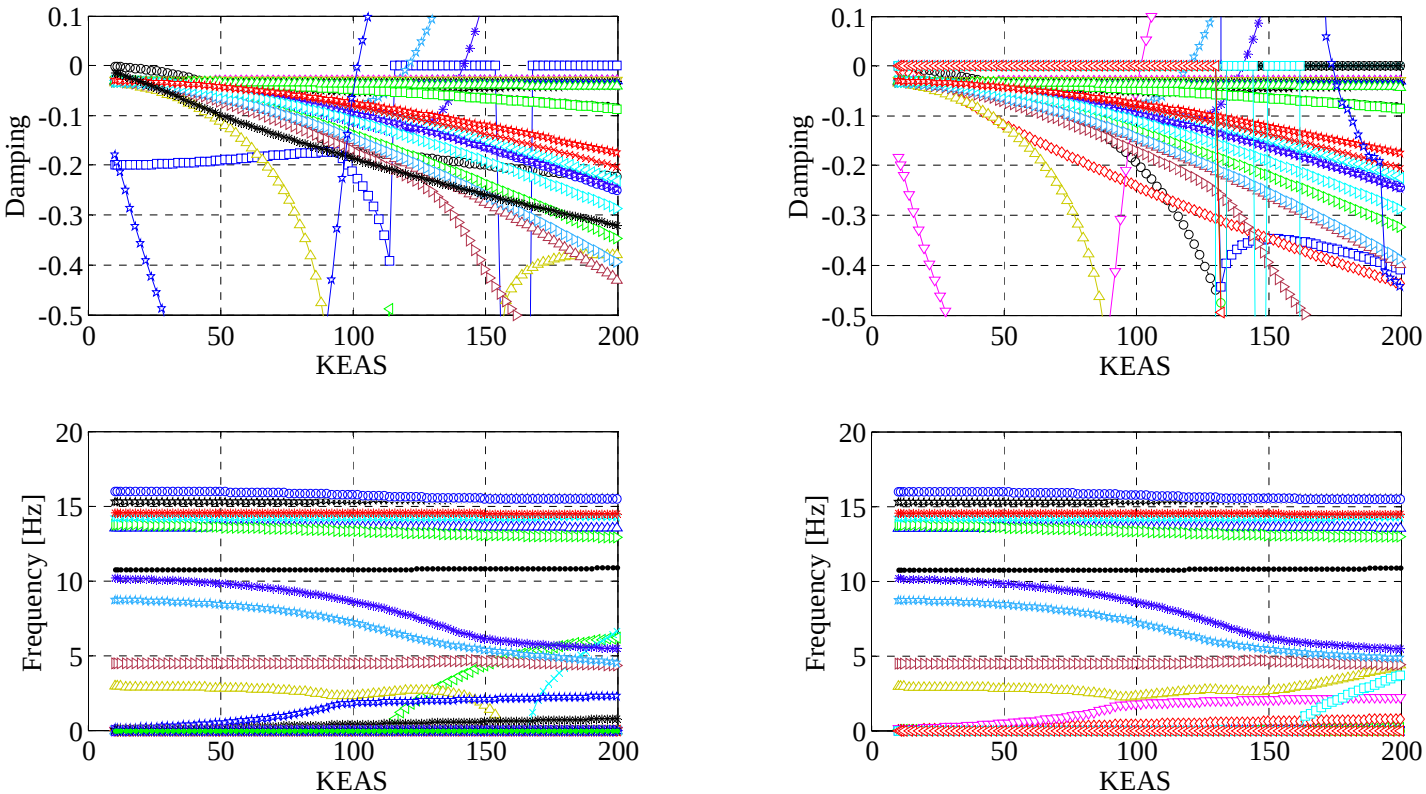


AWBT Mode



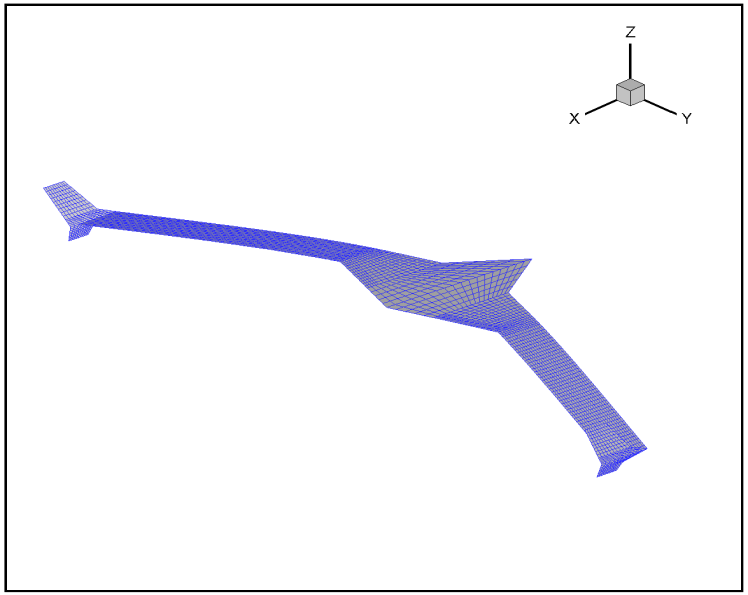
SWBT Mode

Validation of the ASE State-Space Equations for MAD/MUTT at Full Fuel Condition

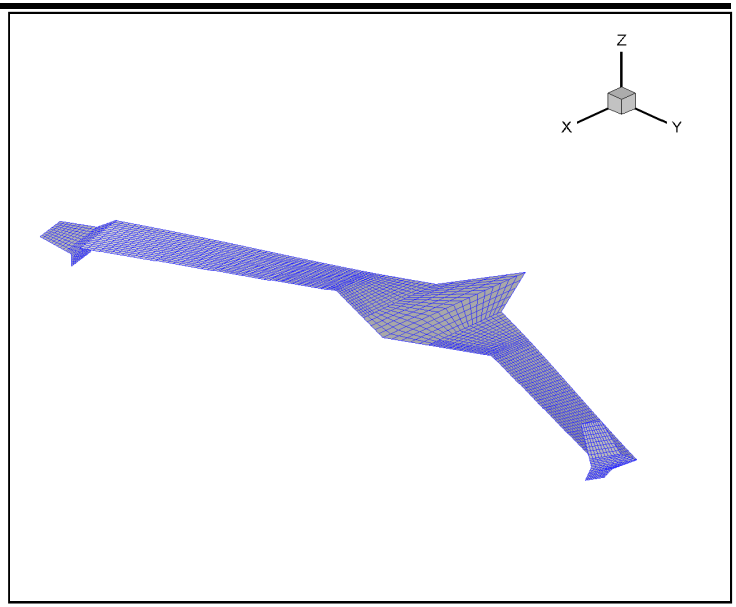


Flexible Full Flutter Mode	ASE		g-method	
	V_f (KEAS)	ω_f (Hz)	V_f (KEAS)	ω_f (Hz)
BFF	102.1	1.80	102.0	1.78
SWBT	121.1	6.24	120.1	6.32
AWBT	141.7	6.48	140.1	6.61

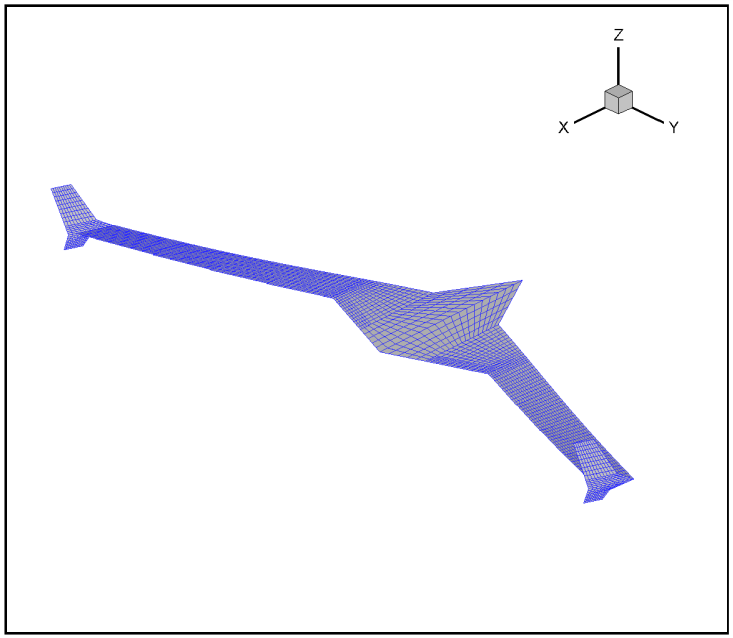
Flutter Modes of the Full Fuel Condition



BFF Mode



AWBT Mode



SWBT Mode

The Original DFS Approach

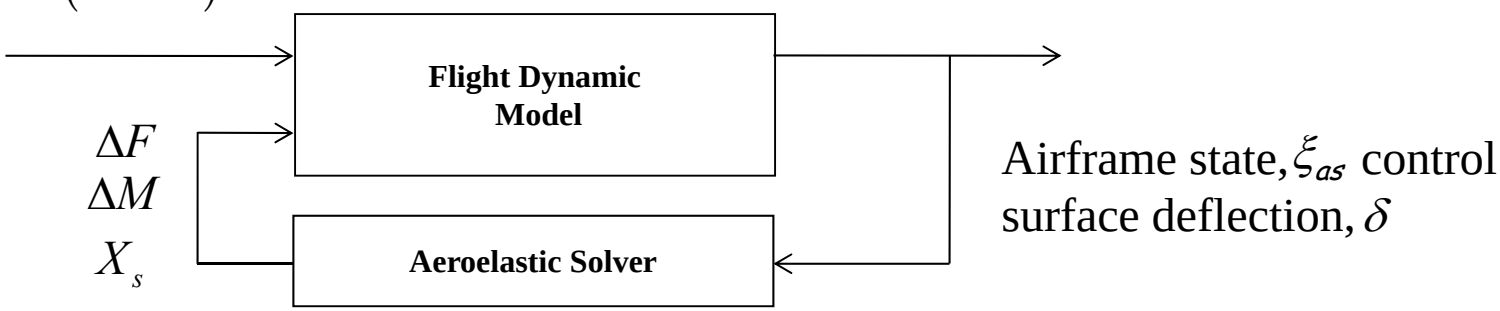
- Partitioning the state-space equations into the airframe states and elastic states.

$$\begin{Bmatrix} \dot{\xi}_{as} \\ \hline \dot{\eta}_e \\ \ddot{\eta}_e \\ \dot{x}_a \end{Bmatrix} = \left[\begin{array}{c|c} A_{rr} & A_{re} \\ \hline A_{er} & A_{ee} \end{array}\right] \begin{Bmatrix} \xi_{as} \\ \hline \eta_e \\ \dot{\eta}_e \\ x_a \end{Bmatrix} + \left[\begin{array}{c} B_r \\ \hline B_e \end{array}\right] \begin{Bmatrix} \delta \\ \dot{\delta} \\ \ddot{\delta} \end{Bmatrix}$$

- The aeroelastic solver solves only the elastic states.

$$\begin{Bmatrix} \dot{\eta}_e \\ \ddot{\eta}_e \\ \dot{x}_a \end{Bmatrix} = \left[A_{ee}\right] \begin{Bmatrix} \eta_e \\ \dot{\eta}_e \\ x_a \end{Bmatrix} + \left[A_{er}\right]\left\{\xi_{as}\right\} + \left[B_e\right] \begin{Bmatrix} \delta \\ \dot{\delta} \\ \ddot{\delta} \end{Bmatrix}$$

- ξ_{as} and $\left(\delta, \dot{\delta}, \ddot{\delta}\right)^T$ are provided by the flight dynamic modes.

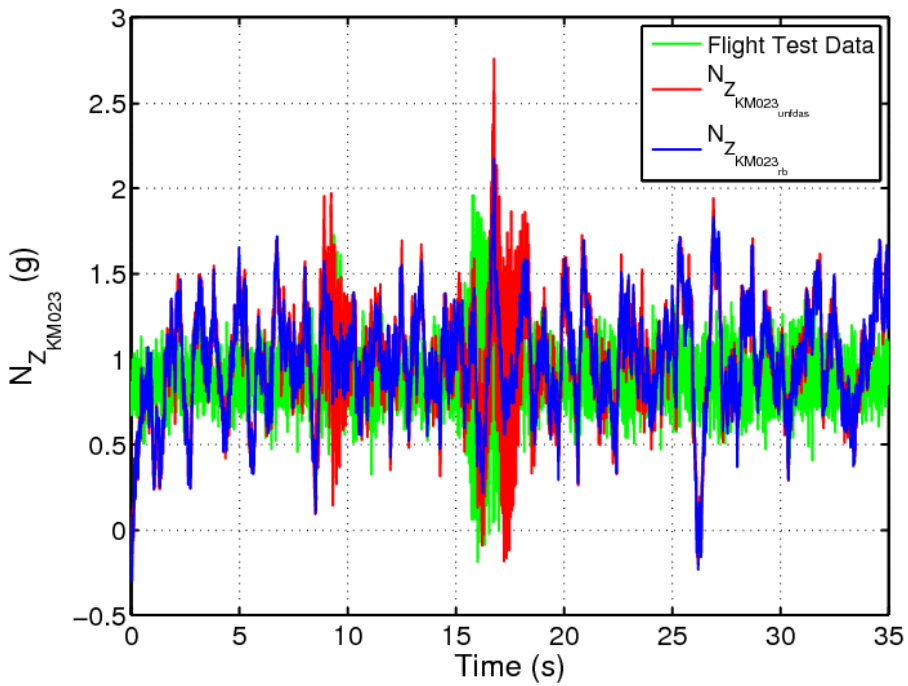


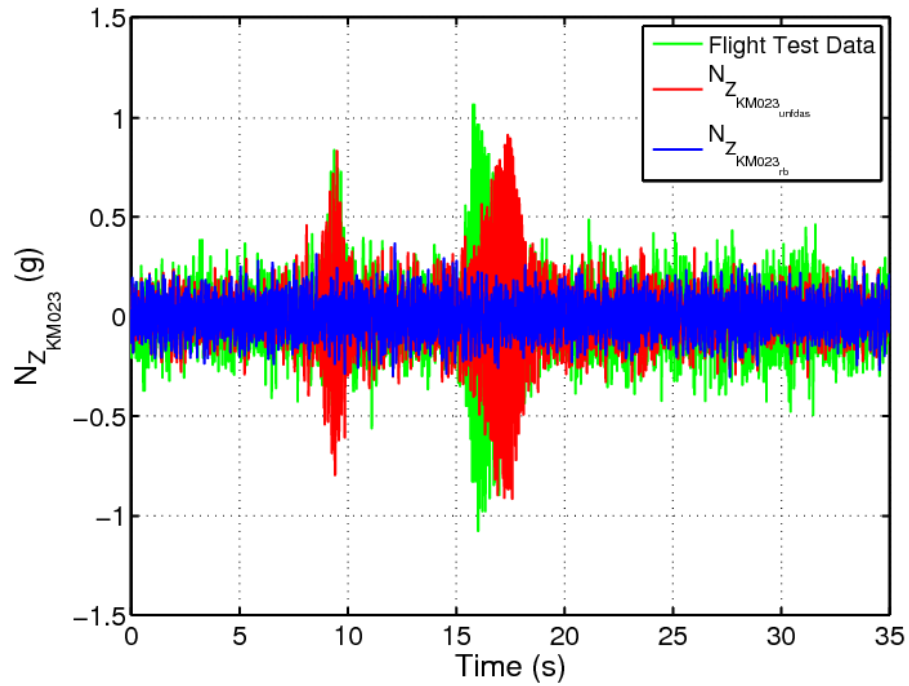
- ΔF and ΔM are obtained from the rigid body sub-matrices of RFA:

$$\begin{Bmatrix} \Delta F \\ \Delta M \end{Bmatrix} = q_\infty \left[\left[A_{0_{re}}\right]\eta_e + \frac{L}{V}\left[A_{1_{re}}\right]\dot{\eta}_e + \left(\frac{L}{V}\right)^2 \left[A_{2_{re}}\right]\ddot{\eta}_e + \left[D_{re}\right]x_a \right]$$

The Original DFS has been Validated with AAW Flight Test Data at M=0.9 and H=15kft

- Input: Collective Aileron (Frequency Sweep, 5-35 Hz, Δ_t = 35 sec)
- Output: acceleration at wing fold



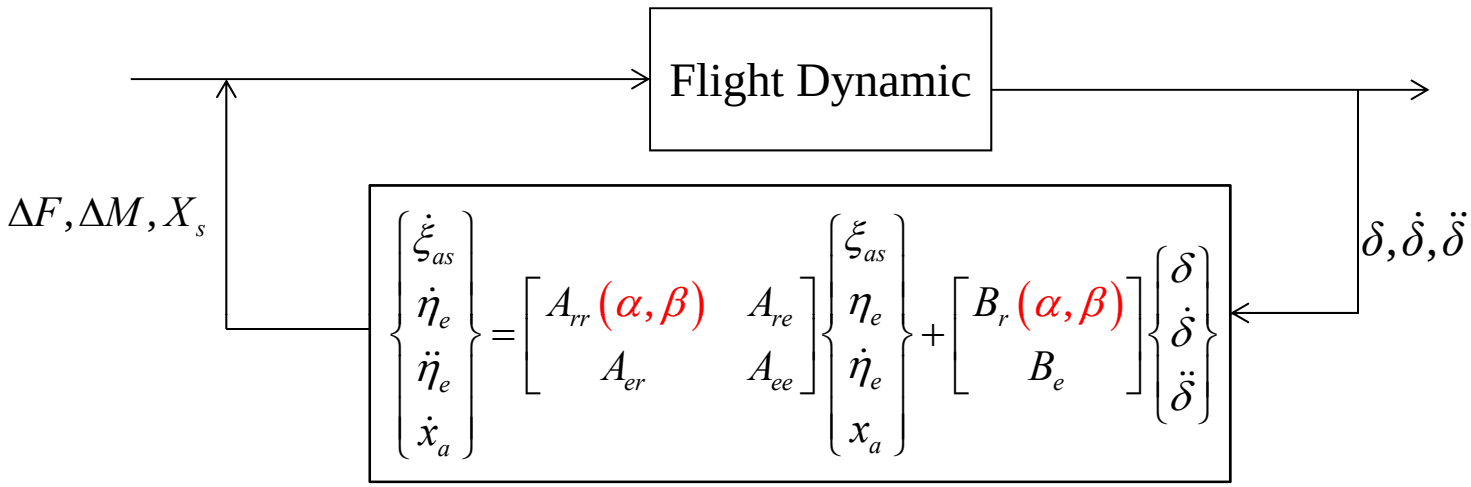


Failure of Original DFS on MAD/MUTT

- The original DFS approach ignores the term $[A_{re}]$ in the aeroelastic solver.
  - Because of the weak coupling between the rigid body and elastic modes of AAW, the original DFS results match with the AAW flight test data.
  - Because of the Body Freedom Flutter (BFF) mode, the original DFS fails to predict BFF of MAD/MUTT.
- This suggests that all coupling terms between rigid body and elastic states must be included in the DFS.

The New DFS Approach for MAD/MUTT

- The ASE state-space equation including airframe states, elastic states and aerodynamic lag states are solved at each time step.



- The input of DFS is δ, $\dot{\delta}$ and $\ddot{\delta}$
- The output of DFS is ΔF, ΔM and X_s
- $A_{rr}(\alpha_i, \beta_j)$ and $B_r(\alpha_i, \beta_j)$ are pre-computed at i = 1, 2, …n and j = 1, 2, …m
  - Rigid body aerodynamic stability derivatives at α_i and β_j are obtained from the aerodynamic database in the flight dynamic model to account for nonlinear rigid body aerodynamic effects.
  - During simulation, $A_{rr}(\alpha, \beta)$ and $B_r(\alpha, \beta)$ are interpolated through $A_{rr}(\alpha_i, \beta_j)$ and $B_r(\alpha_i, \beta_j)$

$\Delta \boldsymbol{F}$ and $\Delta \boldsymbol{M}$ Recovery

- The ΔF and ΔM recovery in the original DFS approach does not work for MAD/MUTT.
  - If $[D]$ matrix in RFA is partitioned into $[D_{rr}\ ,\ D_{er}]$, the effect of D_{rr} is ignored.
  - Without D_{rr}, the BFF mode can not be predicted.
- Instead of computing ΔF and ΔM from RFA, they can be computed from the structural matrices.
  - $$[M_{GG}][\phi_r,\phi_e]\begin{Bmatrix}\ddot{\eta}_r\\ \ddot{\eta}_e\end{Bmatrix}+[K_{GG}][\phi_r,\phi_e]\begin{Bmatrix}\eta_r\\ \eta_e\end{Bmatrix}+[M_{GG}][\phi_c]\left[\ddot{\delta}\right]=F_a$$
  - pre-multiplying by ϕ_r^T yields

$$[\phi_r]^T[M_{GG}][\phi_r]\{\ddot{\eta}_r\}+\cancelto{0}{[\phi_r]^T[M_{GG}][\phi_e]\{\ddot{\eta}_e\}}+\cancelto{0}{[\phi_r]^T[K_{GG}][\phi_r]\{\eta_r\}}$$

$$+\cancelto{0}{[\phi_r]^T[K_{GG}][\phi_e]\{\ddot{\eta}_e\}}+[\phi_r]^T[M_{GG}][\phi_c]\left\{\ddot{\delta}\right\}=[\phi_r]^T F_a$$

  - $$\begin{Bmatrix}\Delta F\\ \Delta M\end{Bmatrix}=[M_{rr}]\{\ddot{\eta}_r\}+[M_{rc}]\left\{\ddot{\delta}\right\}$$

Comparison of Approaches

Original Approach

- Solves elastic states only
- Input: ξ_{as} and δ from flight dynamic model
- Output: ΔF and ΔM computed from aerodynamic matrices
- Cannot predict BFF

New Approach

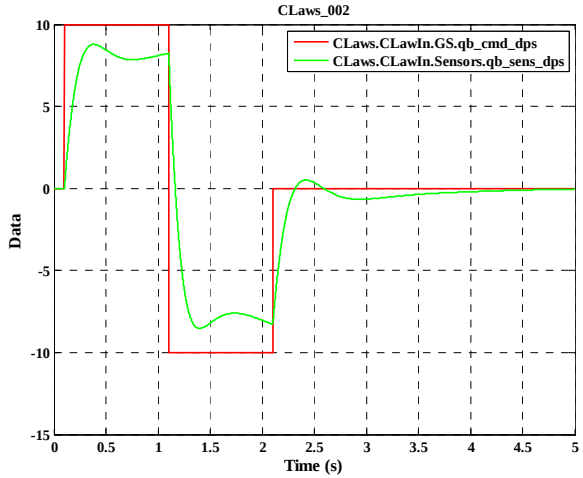
- Solves rigid body and elastic states simultaneously
- Input: δ only from flight dynamic model
- Output: ΔF and ΔM computed from structural matrices
- Can predict BFF

Flexible Full Fuel Simulation

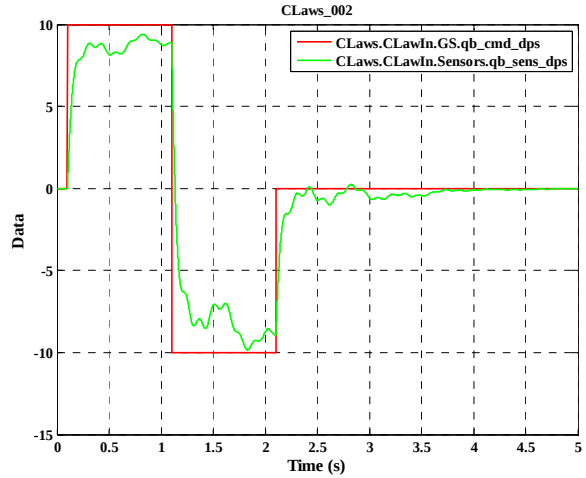
- ZAERO flutter prediction is 2043 ft, 1.78 Hz
- ASE flutter prediction is 1934 ft, 1.80 Hz
- DFS altitude is set to 0, 2000, and 10000 ft

Pitch Rate, q, Command and Sensor (deg/s)

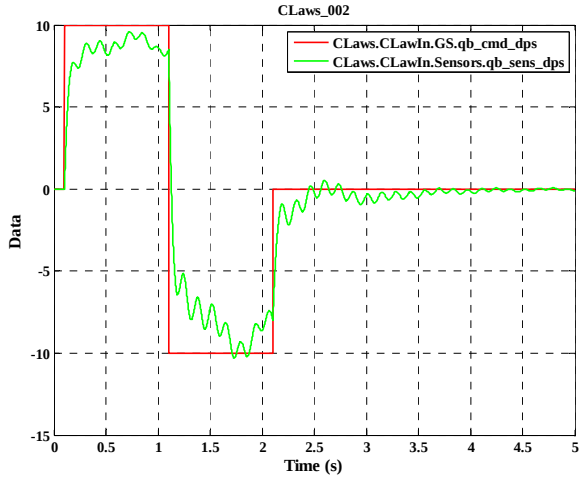
No DFS



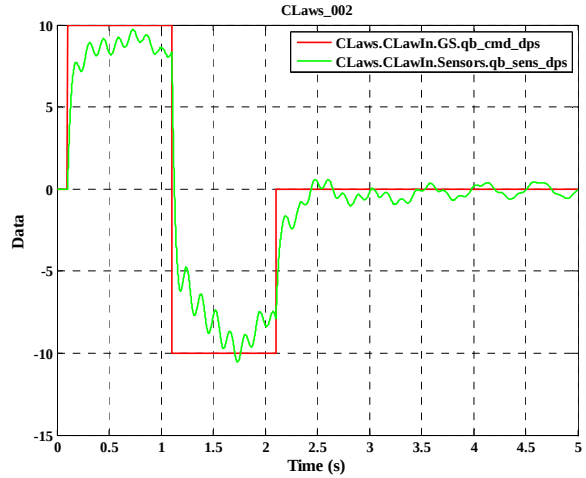
10,000 ft



2000 ft

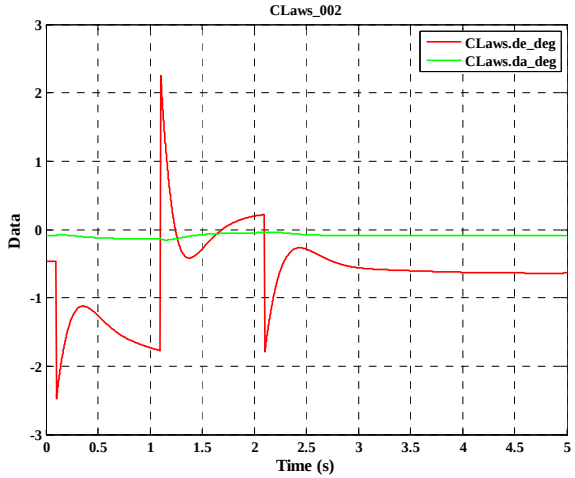


0 ft

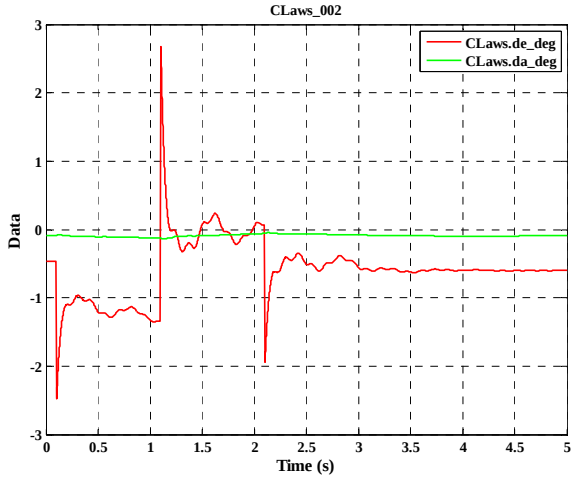


Sym and Antisym Control Command (deg)

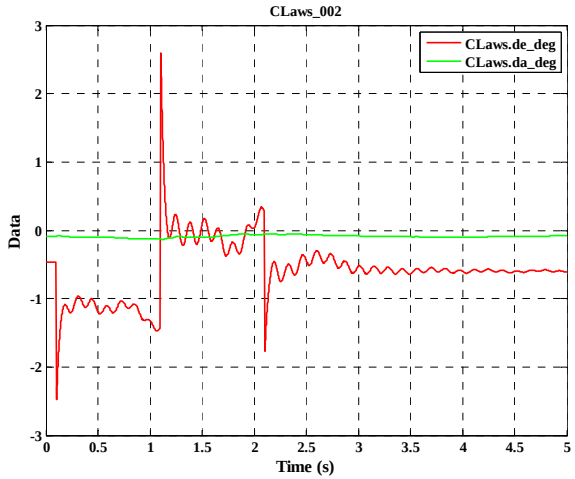
No DFS



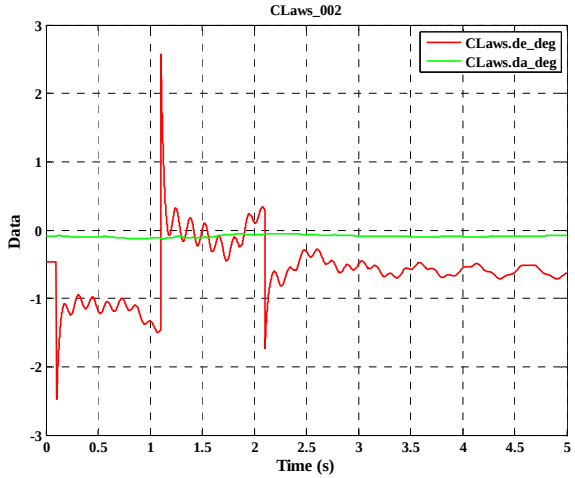
10,000 ft



2000 ft

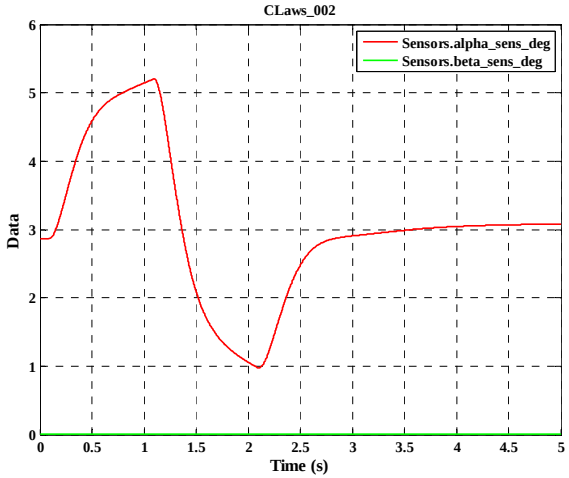


0 ft

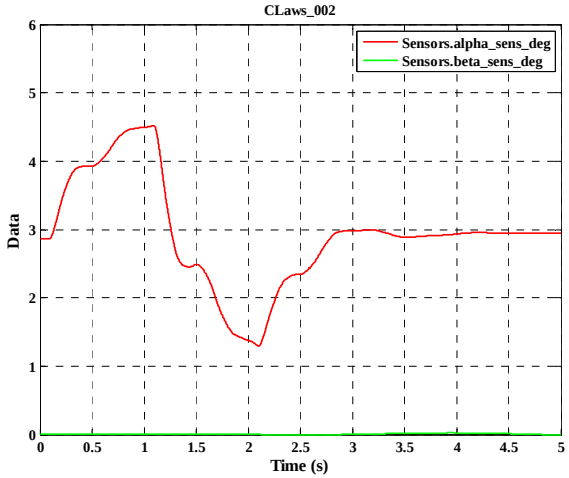


Alpha and Beta Sensor (deg)

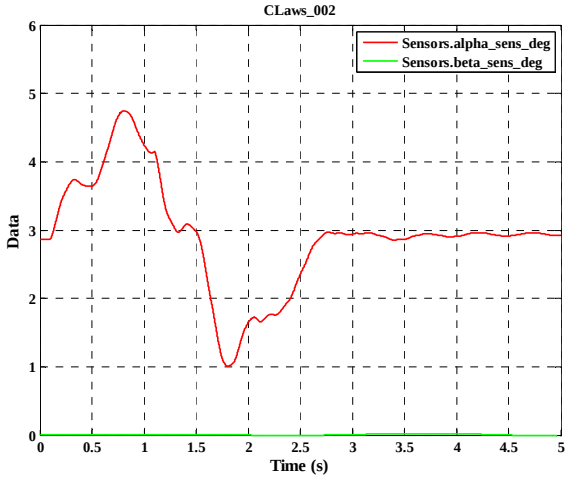
No DFS



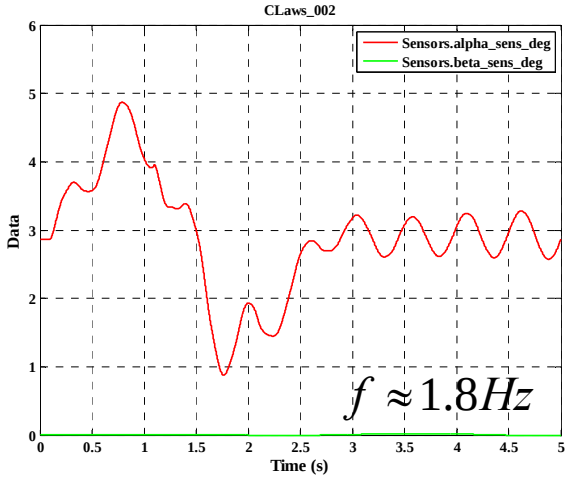
10,000 ft



2000 ft

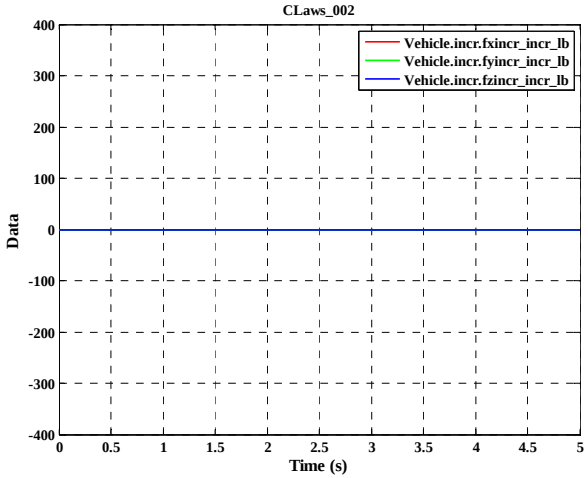


0 ft

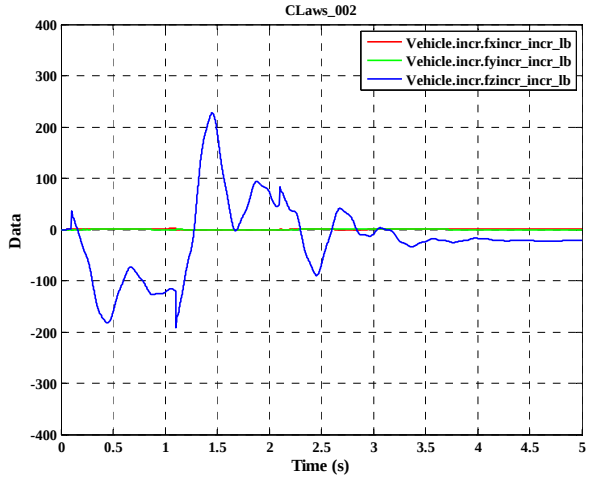


Incremental Forces, ΔF_x, ΔF_y, ΔF_z (lb)

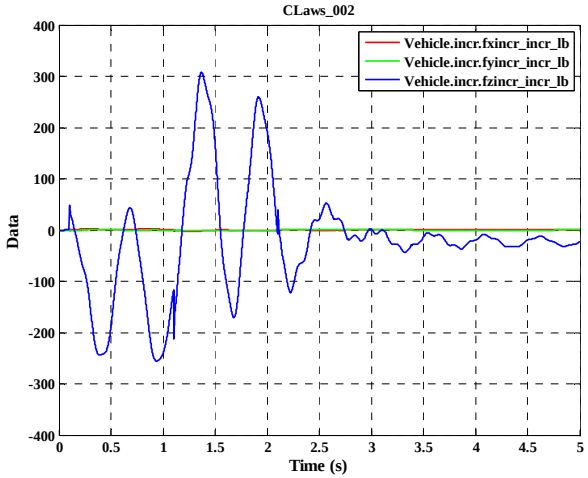
No DFS



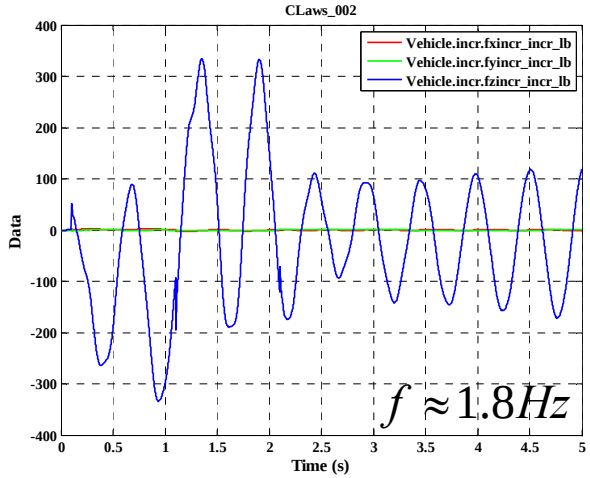
10,000 ft



2000 ft

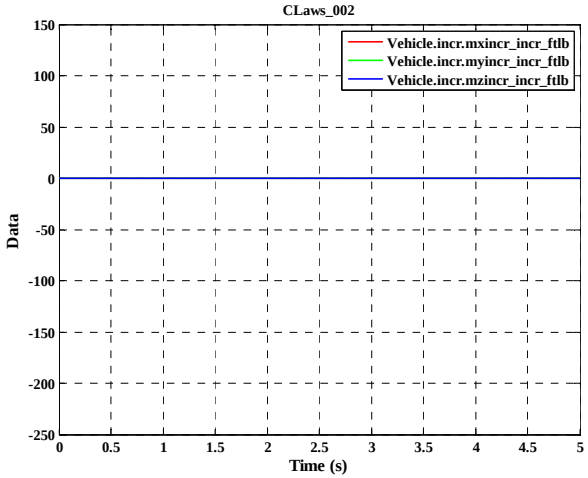


0 ft

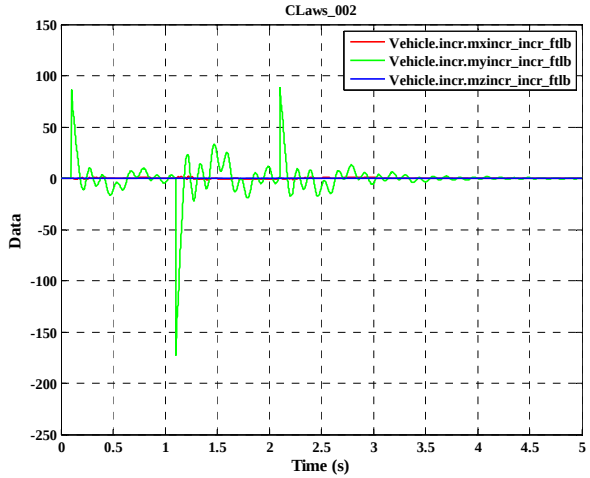


Incremental Moments, ΔM_x, ΔM_y, ΔM_z (ft lb)

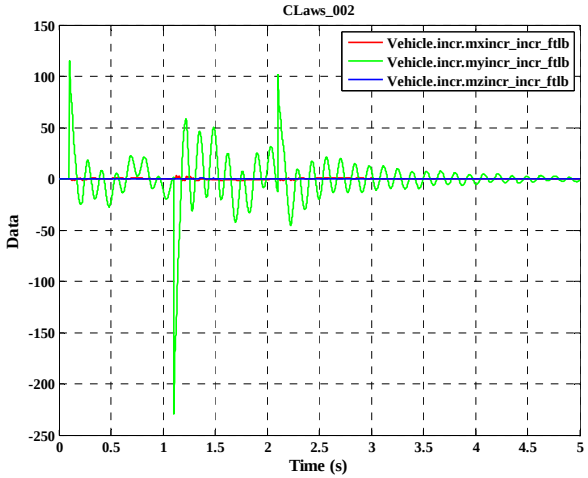
No DFS



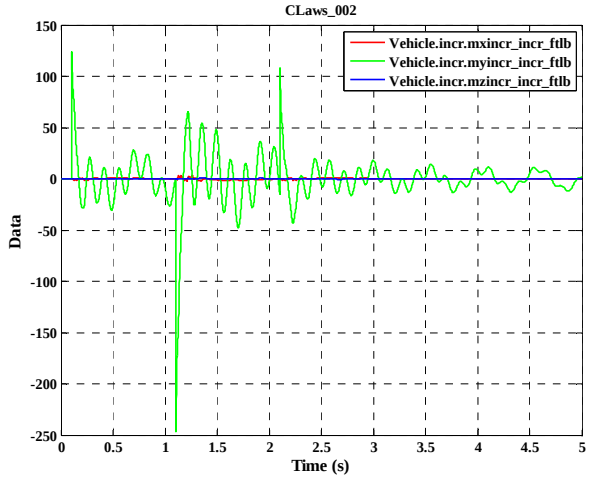
10,000 ft



2000 ft



0 ft

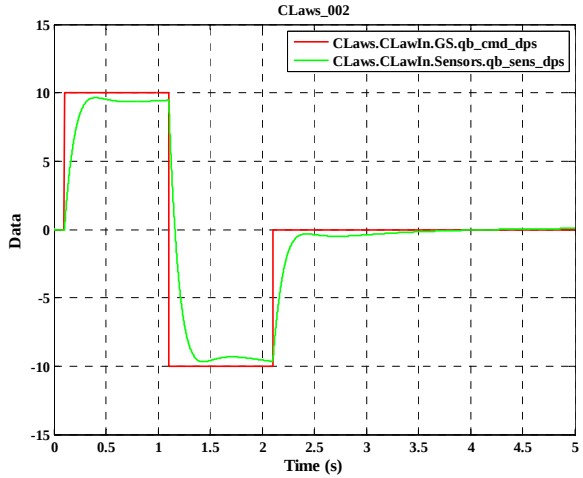


Flexible Empty Fuel Simulation

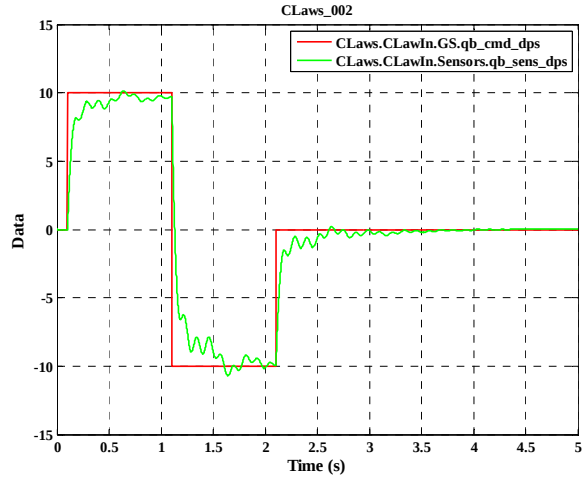
- ZAERO flutter prediction is 1044 ft, 2.56 Hz
- ASE flutter prediction is 728 ft, 2.58 Hz
- DFS altitude is set to -1000, 1000, and 10000 ft

Pitch Rate, q, Command and Sensor (deg/s)

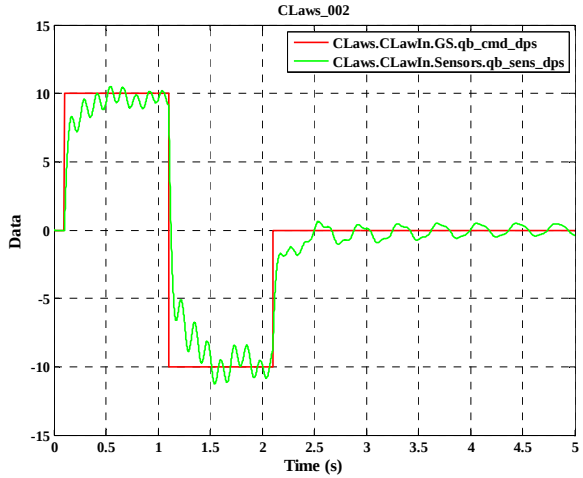
No DFS



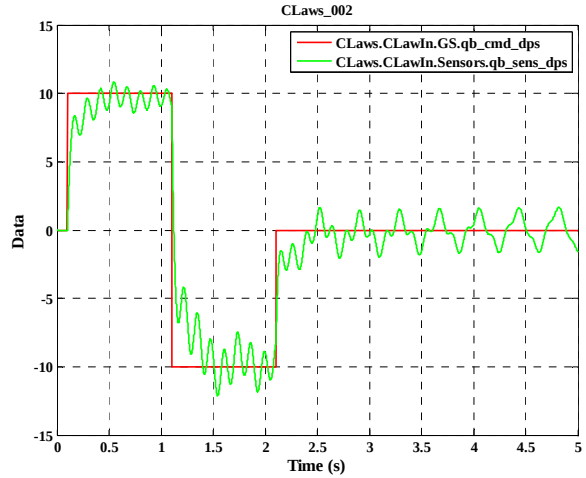
10,000 ft



1000 ft

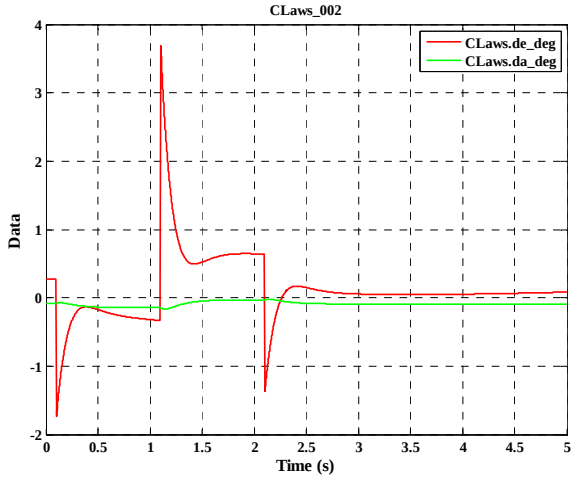


-1000 ft

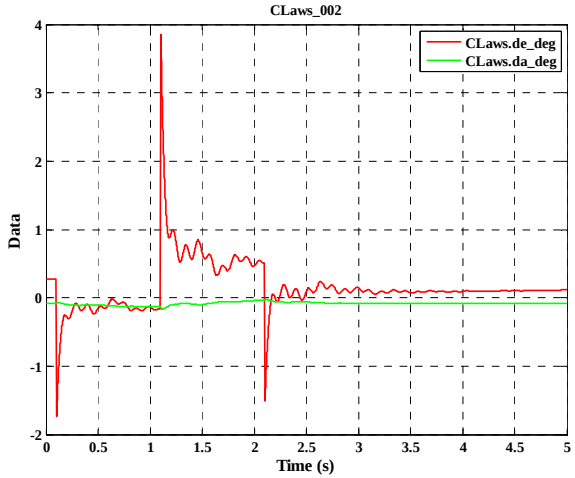


Sym and Antisym Control Command (deg)

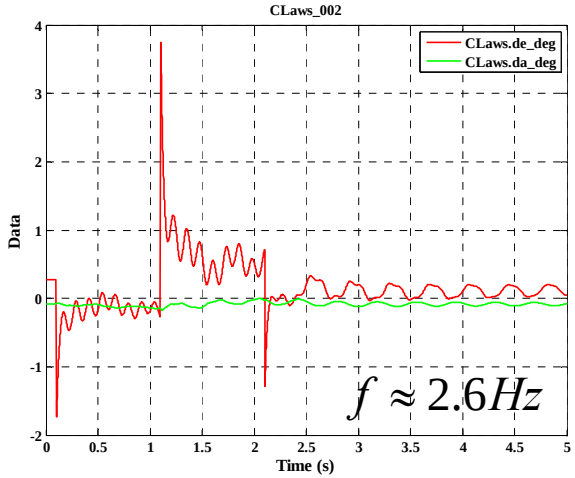
No DFS



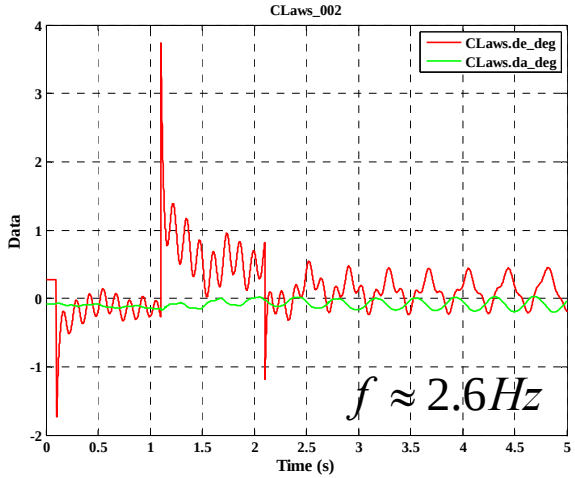
10,000 ft



1000 ft

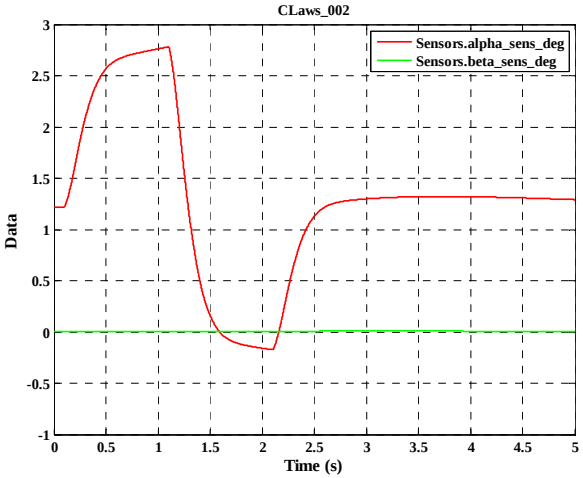


-1000 ft

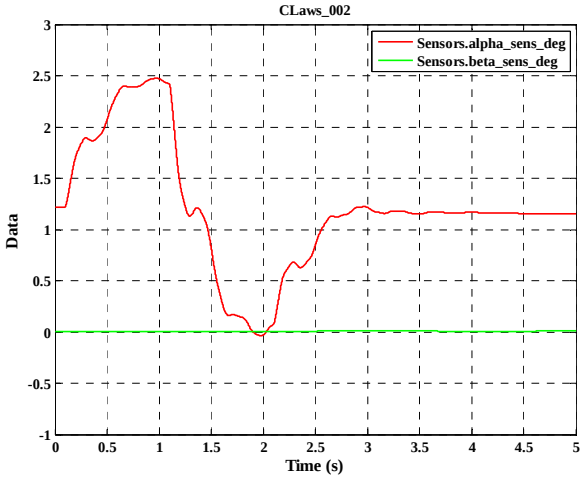


Alpha and Beta Sensor (deg)

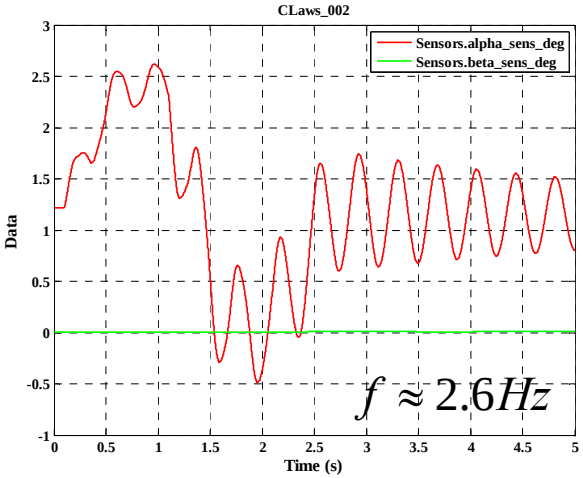
No DFS



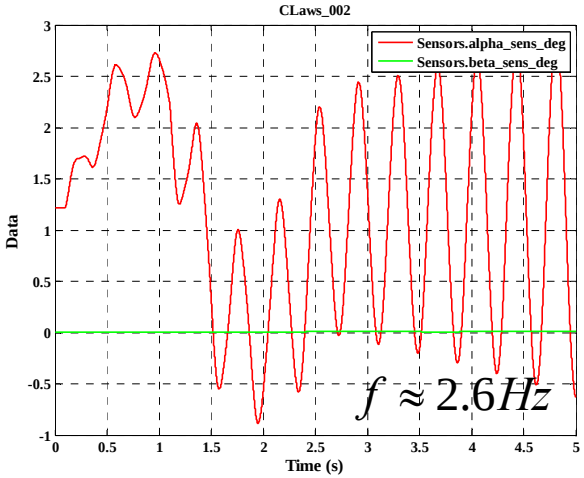
10,000 ft



1000 ft

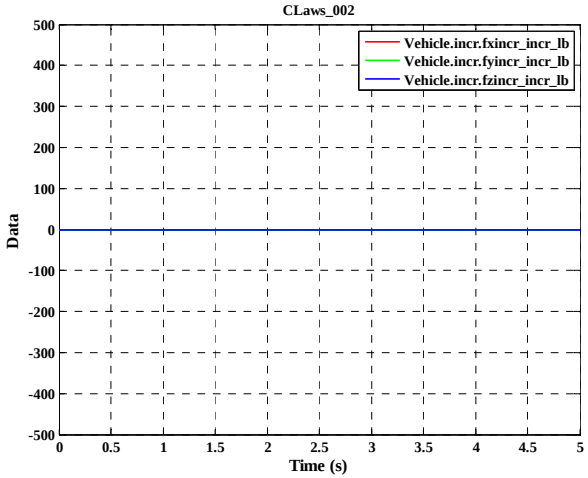


-1000 ft

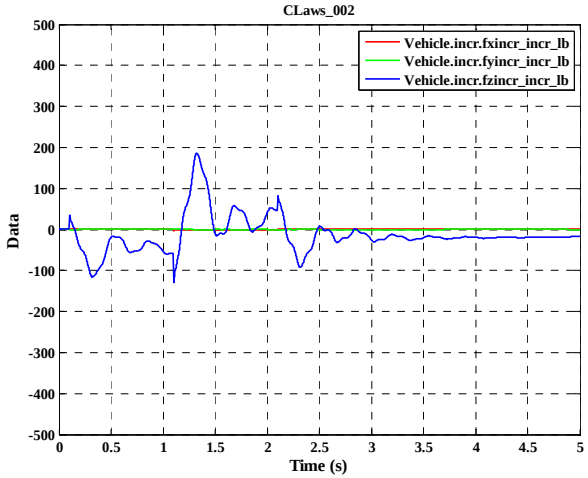


Incremental Forces, ΔF_x, ΔF_y, ΔF_z (lb)

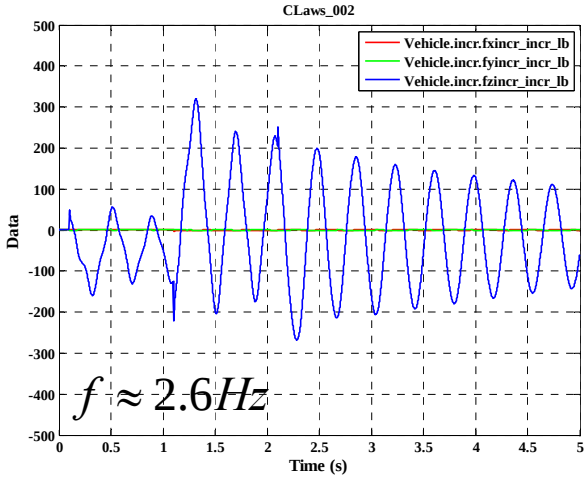
No DFS



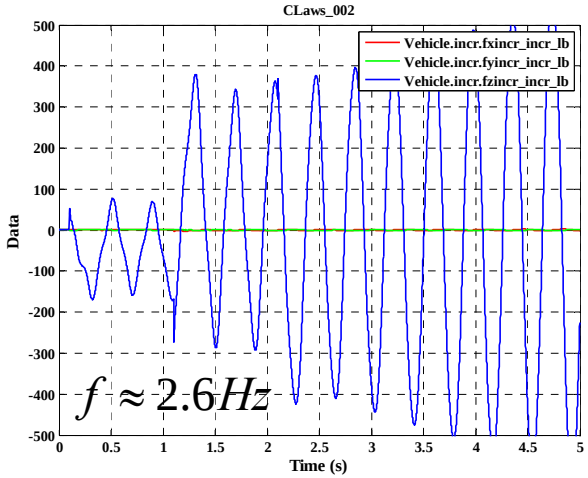
10,000 ft



1000 ft

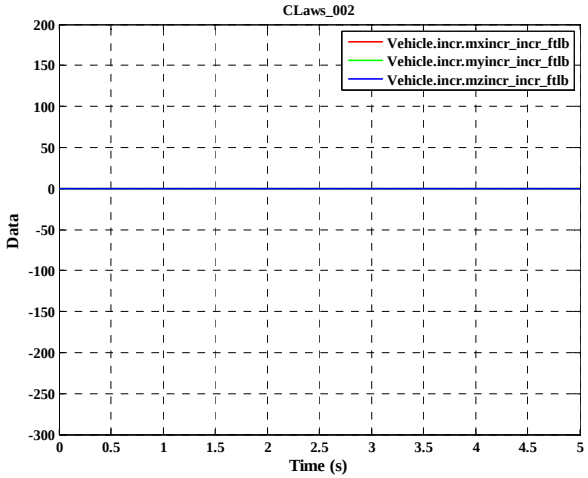


-1000 ft

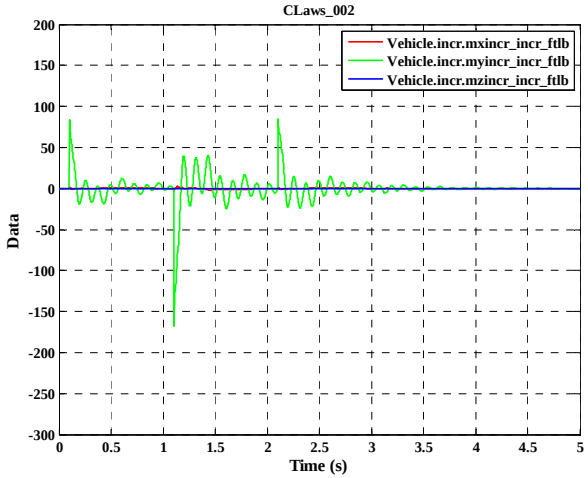


Incremental Moments, ΔM_x, ΔM_y, ΔM_z (ft lb)

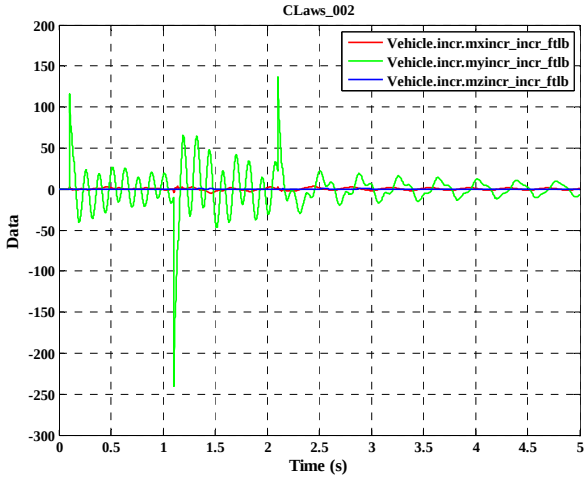
No DFS



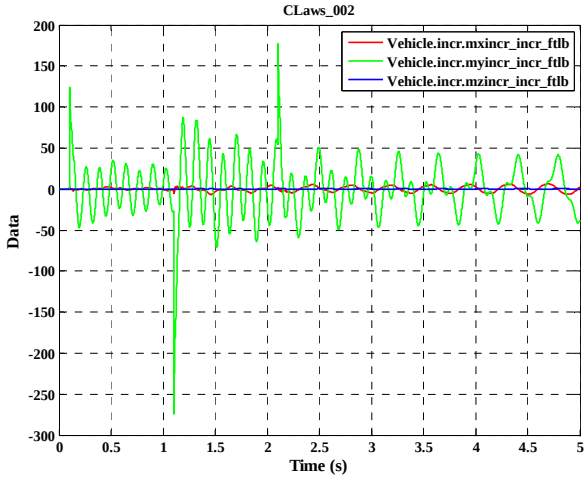
10,000 ft



1000 ft



-1000 ft



Future Work

- DFS can be used to evaluate the performance of flutter suppression and gust loads alleviation controllers for MAD/MUTT.

- So far, the state-space equation in DFS is constructed by the natural modes of each fuel condition.
  - DFS is defined in different modal coordinates at different fuel conditions.
  - This allows DFS to perform simulation only one point in the sky at one time.

- If the state-space equations at all fuel conditions are constructed by one set of natural modes, for instance of the full fuel condition, DFS can perform a continuous simulation at all flight conditions by a multi-dimensional interpolation.
  - Through Mach number and altitudes
  - Through angles of attack and side slip angles
  - Through fuel conditions

- Because of the real-time computational capability of DFS, DFS can be plugged into a real-time simulator to train the pilot under aeroelastic effects.