Dynamic Flight Simulation (DFS) for MAD/MUTT

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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 “flexibilized” 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, $\Delta F$ and $\Delta M$, 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.
The frequency-domain \( (k) \) Generalized Aerodynamics Forces (GAF) are transformed to the time domain via the Rational Function Approximation (RFA).

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

where \( \{x_a\} = \left[ I \right] S - \frac{V}{L} \left[ R \right] \right]^{-1} \left[ E_h, E_c \right] S \) 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:

\[
\begin{align*}
& \left[ M_{hh} \right] \{\ddot{\xi}\} + \left[ C_{hh} \right] \{\dot{\xi}\} + \left[ K_{hh} \right] \{\xi\} + \left[ M_{hc} \right] \{\ddot{\delta}\} \\
& = q_\infty \left[ A_{hh_0} \right] \{\ddot{\xi}\} + \frac{L}{V} \left[ A_{hh_1} \right] \{\dot{\xi}\} + \frac{L^2}{V^2} \left[ A_{hh_2} \right] \{\xi\} \\
& + q_\infty \left[ A_{hc_0} \right] \{\ddot{\delta}\} + \frac{L}{V} \left[ A_{hc_1} \right] \{\dot{\delta}\} + \frac{L^2}{V^2} \left[ A_{hc_2} \right] \{\delta\} + q_\infty [D] \{x_a\}
\end{align*}
\]
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
\[ \{ U_{ae} \} = \{ \delta, \dot{\delta}, \ddot{\delta} \}^T \]

\[
[A_{ae}] =
\begin{bmatrix}
[0] & [I] & [0] \\
-\left[ \bar{M} \right]^{-1} \left[ \left[ K_{hh} \right] - q_\infty \left[ A_{hh0} \right] \right] -\left[ \bar{M} \right]^{-1} \left[ C_{hh} \right] - q_\infty \frac{L}{V} \left[ A_{hh} \right] & q_\infty \left[ \bar{M} \right]^{-1} \left[ D \right] \\
[0] & [E_h] & \frac{V}{L} [R] \\
\end{bmatrix}
\]

\[
[B_{ae}] =
\begin{bmatrix}
q_\infty \left[ \bar{M} \right]^{-1} \left[ A_{hc0} \right] & q_\infty \frac{L}{V} \left[ \bar{M} \right]^{-1} \left[ A_{hc1} \right] \frac{L}{V} \left[ \bar{M} \right]^{-1} \left[ A_{hc2} \right] \\
0 & [E_c] & 0 \\
\end{bmatrix}
\]

\[ \bar{M} = \left[ M_{hh} \right] - \frac{q_\infty L^2}{V^2} \left[ A_{hh2} \right] \]

- The number of states is \( 2 \times N_h + N_{lag} \) if the Minimum State Method is used and is \( 2 \times N_h \times N_{lag} \) 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 $\eta_q$ to airframe status $\xi_{as}$.

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

\[
\{\eta_q\} = \{q_1, q_2, \ldots q_6\}
\]

\[
\Rightarrow \{\eta\} = [R_p]^{-1} [R_B]\{\eta_r\}
\]

Rigid Body d.o.f. in Body Axis:

Airframe States:

For Symmetric Maneuvers $[T_A]$ is defined as:

\[
\begin{bmatrix}
T_x \\
T_z \\
R_y \\
\dot{T}_x \\
\dot{T}_z \\
\dot{R}_y
\end{bmatrix} =
\begin{bmatrix}
-1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 \\
0 & -1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -V_\infty & V_\infty & 0 \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
\begin{bmatrix}
x \\
u \\
h \\
\alpha \\
\beta \\
\phi
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & -1 \\
0 & V_\infty & 0 & 0 & 0 & V_\infty \\
0 & 0 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & -1 & 0 & 0
\end{bmatrix}
\]

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

\[
\begin{bmatrix}
T_y \\
R_x \\
R_z \\
\dot{T}_y \\
\dot{R}_x \\
\dot{R}_z
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & -1 \\
0 & V_\infty & 0 & 0 & 0 & V_\infty \\
0 & 0 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & -1 & 0 & 0
\end{bmatrix}
\]
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.

\[
[M] = \begin{bmatrix}
M_{rb} & 0 \\
0 & M_{ee}
\end{bmatrix}
\]

where matrices \([M_{rb}]\) and \([M_{ee}]\) are defined as,

\[
[M_{rb}] = \begin{bmatrix}
m & 0 & 0 & 0 & 0 & 0 \\
0 & m & 0 & 0 & 0 & 0 \\
0 & 0 & m & 0 & 0 & 0 \\
0 & 0 & 0 & I_{xx} & 0 & I_{xz} \\
0 & 0 & 0 & 0 & I_{yy} & 0 \\
0 & 0 & 0 & I_{xz} & 0 & I_{zz}
\end{bmatrix}, \quad [M_{ee}] = \begin{bmatrix}\ddots & \ddots & \ddots \\
\vdots & \ddots & \ddots \\
\vdots & \ddots & \ddots \\
\end{bmatrix}
\]

\(m\) 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.

\[
[A_0] = \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & \frac{mg}{q_x} \cos \phi_o & 0 \\
0 & 0 & -S(C_{D_a} - C_{D_v}) - \frac{mg}{q_x} \cos \phi_o & -SC_{D_\beta} \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\]

\[
[A] = \begin{bmatrix}
\frac{2S(C_{D_a} + C_{D_v})}{(\frac{1}{2})} & \frac{-SC_{D_\theta}}{(\frac{1}{2})} & \frac{S(C_{D_a} - C_{D_v})}{(\frac{1}{2})} & \frac{-0.5SbC_{D_p}}{(\frac{1}{2})} & \frac{-0.5Sc(C_{D_a} + C_{D_v})}{(\frac{1}{2})} & \frac{-0.5Sb(C_{D_\alpha} + C_{D_\beta})}{(\frac{1}{2})} \\
\frac{2S(C_{L_a} + C_{L_v})}{(\frac{1}{2})} & \frac{-SC_{L_\theta}}{(\frac{1}{2})} & \frac{SC_{L_\theta}}{(\frac{1}{2})} & \frac{-0.5SbC_{L_p}}{(\frac{1}{2})} & \frac{-0.5Sc(C_{L_a} + C_{L_v})}{(\frac{1}{2})} & \frac{-0.5Sb(C_{L_\alpha} + C_{L_\beta})}{(\frac{1}{2})} \\
\frac{2S(C_{L_a} + C_{L_v})}{(\frac{1}{2})} & \frac{-SC_{L_\theta}}{(\frac{1}{2})} & \frac{S(C_{L_a} + C_{D_a})}{(\frac{1}{2})} & \frac{-0.5SbC_{L_p}}{(\frac{1}{2})} & \frac{-0.5Sc(C_{L_a} + C_{D_v})}{(\frac{1}{2})} & \frac{-0.5Sb(C_{L_\alpha} + C_{D_\beta})}{(\frac{1}{2})} \\
\frac{2S(C_{L_a} + C_{L_v})}{(\frac{1}{2})} & \frac{-SC_{L_\theta}}{(\frac{1}{2})} & \frac{S(C_{L_a} + C_{D_a})}{(\frac{1}{2})} & \frac{-0.5SbC_{L_p}}{(\frac{1}{2})} & \frac{-0.5Sc(C_{L_a} + C_{D_v})}{(\frac{1}{2})} & \frac{-0.5Sb(C_{L_\alpha} + C_{D_\beta})}{(\frac{1}{2})} \\
\frac{2S(C_{L_a} + C_{L_v})}{(\frac{1}{2})} & \frac{-SC_{L_\theta}}{(\frac{1}{2})} & \frac{S(C_{L_a} + C_{D_a})}{(\frac{1}{2})} & \frac{-0.5SbC_{L_p}}{(\frac{1}{2})} & \frac{-0.5Sc(C_{L_a} + C_{D_v})}{(\frac{1}{2})} & \frac{-0.5Sb(C_{L_\alpha} + C_{D_\beta})}{(\frac{1}{2})} \\
\frac{2S(C_{L_a} + C_{L_v})}{(\frac{1}{2})} & \frac{-SC_{L_\theta}}{(\frac{1}{2})} & \frac{S(C_{L_a} + C_{D_a})}{(\frac{1}{2})} & \frac{-0.5SbC_{L_p}}{(\frac{1}{2})} & \frac{-0.5Sc(C_{L_a} + C_{D_v})}{(\frac{1}{2})} & \frac{-0.5Sb(C_{L_\alpha} + C_{D_\beta})}{(\frac{1}{2})}
\end{bmatrix}_{6 \times 6}
\]

- 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.

<table>
<thead>
<tr>
<th>Flexible Empty Flutter Mode</th>
<th>ASE</th>
<th>g-method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_f$ (KEAS)</td>
<td>$\omega_f$ (Hz)</td>
</tr>
<tr>
<td>BFF</td>
<td>104.4</td>
<td>2.58</td>
</tr>
<tr>
<td>AWBT</td>
<td>116.9</td>
<td>4.70</td>
</tr>
<tr>
<td>SWBT</td>
<td>118.7</td>
<td>6.66</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Flexible Full Flutter Mode</th>
<th>ASE</th>
<th>g-method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_f$ (KEAS)</td>
<td>$\omega_f$ (Hz)</td>
</tr>
<tr>
<td>BFF</td>
<td>102.1</td>
<td>1.80</td>
</tr>
<tr>
<td>SWBT</td>
<td>121.1</td>
<td>6.24</td>
</tr>
<tr>
<td>AWBT</td>
<td>141.7</td>
<td>6.48</td>
</tr>
</tbody>
</table>
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.

\[
\begin{align*}
\begin{bmatrix}
\dot{\xi}_{as} \\
\dot{\eta}_e \\
\dot{\eta}_e \\
\dot{x}_a
\end{bmatrix} &=
\begin{bmatrix}
A_{rr} & A_{re} \\
A_{er} & A_{ee}
\end{bmatrix}
\begin{bmatrix}
\xi_{as} \\
\eta_e \\
\eta_e \\
x_a
\end{bmatrix} +
\begin{bmatrix}
B_r \\
B_e
\end{bmatrix}
\begin{bmatrix}
\delta \\
\dot{\delta} \\
\ddot{\delta}
\end{bmatrix},
\end{align*}
\]

- The aeroelastic solver solves only the elastic states.

\[
\begin{align*}
\begin{bmatrix}
\dot{\eta}_e \\
\ddot{\eta}_e \\
\dot{x}_a
\end{bmatrix} &= [A_{ee}]
\begin{bmatrix}
\eta_e \\
\eta_e \\
x_a
\end{bmatrix} + [A_{er}]
\begin{bmatrix}
\xi_{as} \\
\eta_e \\
\eta_e \\
x_a
\end{bmatrix} + [B_e]
\begin{bmatrix}
\delta \\
\dot{\delta} \\
\ddot{\delta}
\end{bmatrix},
\end{align*}
\]

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

- \(\Delta F\) and \(\Delta M\) are obtained from the rigid body sub-matrices of RFA:

\[
\begin{align*}
\begin{bmatrix}
\Delta F \\
\Delta M
\end{bmatrix} &= q_\infty
\begin{bmatrix}
A_{0_re} & \frac{L}{V} & A_{1_re} & \left(\frac{L}{V}\right)^2 & A_{2_re} & D_{re}
\end{bmatrix}
\begin{bmatrix}
\eta_e \\
\eta_e \\
\eta_e \\
x_a
\end{bmatrix}.
\end{align*}
\]
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, $\Delta t = 35$ 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.

\[ \Delta F, \Delta M, X_s \]

\[ \begin{pmatrix} \dot{\xi}_{as} \\ \dot{\eta}_e \\ \ddot{\eta}_e \\ \dot{x}_a \end{pmatrix} = \begin{bmatrix} A_{rr}(\alpha, \beta) & A_{re} \\ A_{er} & A_{ee} \end{bmatrix} \begin{pmatrix} \xi_{as} \\ \eta_e \\ \dot{\eta}_e \\ x_a \end{pmatrix} + \begin{bmatrix} B_r(\alpha, \beta) \end{bmatrix} \begin{pmatrix} \delta \\ \dot{\delta} \\ \ddot{\delta} \end{pmatrix} \]

- The input of DFS is \( \delta, \dot{\delta}, \ddot{\delta} \)

- The output of DFS is \( \Delta F, \Delta M \) and \( X_s \)

- \( A_{rr}(\alpha_i, \beta_j) \) and \( B_r(\alpha_i, \beta_j) \) are pre-computed at \( i = 1, 2, \ldots n \) and \( j = 1, 2, \ldots m \)
  - Rigid body aerodynamic stability derivatives at \( \alpha_i \) and \( \beta_j \) 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 \( B_r(\alpha_i, \beta_j) \)
**ΔF and ΔM 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.

\[
\begin{align*}
\text{− } [M_{GG}][\phi_r, \phi_e]\{\ddot{\eta}_r\} + [K_{GG}][\phi_r, \phi_e]\{\eta_e\} + [M_{GG}][\phi_c][\ddot{\delta}] &= F_a \\
\text{− } \text{pre-multiplying by } \phi_r^T \text{ yields} \\
[\phi_r]^T[M_{GG}][\phi_r]\{\ddot{\eta}_r\} + [\phi_r]^T[M_{GG}][\phi_e]\{\ddot{\eta}_e\} + [\phi_r]^T[K_{GG}][\phi_c]\{\ddot{\eta}_c\} + [\phi_r]^T[M_{GG}][\phi_c]\{\ddot{\delta}\} &= [\phi_r]^T F_a \\
\Delta F \begin{cases} \\
\Delta M \end{cases} &= [M_{rr}][\ddot{\eta}_r] + [M_{rc}][\ddot{\delta}]
\end{align*}
\]

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# Comparison of Approaches

<table>
<thead>
<tr>
<th>Original Approach</th>
<th>New Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Solves elastic states only</td>
<td>• Solves rigid body and elastic states simultaneously</td>
</tr>
<tr>
<td>• Input: $\xi_{as}$ and $\delta$ from flight dynamic model</td>
<td>• Input: $\delta$ only from flight dynamic model</td>
</tr>
<tr>
<td>• Output: $\Delta F$ and $\Delta M$ computed from aerodynamic matrices</td>
<td>• Output: $\Delta F$ and $\Delta M$ computed from structural matrices</td>
</tr>
<tr>
<td>• Cannot predict BFF</td>
<td>• Can predict BFF</td>
</tr>
</tbody>
</table>
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)
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

\[ f \approx 1.8 \text{Hz} \]
Incremental Forces, $\Delta F_x$, $\Delta F_y$, $\Delta F_z$ (lb)

No DFS

10,000 ft

2000 ft

0 ft

$f \approx 1.8\text{Hz}$
Incremental Moments, $\Delta M_x$, $\Delta M_y$, $\Delta M_z$ (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

\( f \approx 2.6 \text{Hz} \)
Alpha and Beta Sensor (deg)

No DFS

10,000 ft

1000 ft

-1000 ft

\[ f \approx 2.6 \text{Hz} \]
Incremental Forces, $\Delta F_x$, $\Delta F_y$, $\Delta F_z$ (lb)

No DFS

10,000 ft

1000 ft

-1000 ft

$\approx 2.6 \text{Hz}$
Incremental Moments, $\Delta M_x$, $\Delta M_y$, $\Delta M_z$ (ft lb)
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.