Dynamic Response of Aeroservoelastic Systems with Nonlinear Elements

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Background

- Most common structural and aeroelastic analysis and design tools in the aeronautical industry are linear.
- Introduction of nonlinear effects is usually based on ad-hoc, problem-dependent formulation and simulation processes.
- Nonlinear high-fidelity models are often inefficient and are not naturally integrated in the industrial design processes.
- Reduced-order modeling (ROM) approaches may provide adequate solutions but they are often:
  - lack physical interpretation
  - too specific
  - result in over-simplified linearization
  - hard to be integrated in existing design processes
  - engineers are too conservative or do not have the resources to try them out.
The Increased-Order-Modeling (IOM) Approach

- Start with linear aeroelastic models.
- Identify phenomena of potentially important nonlinear effects.
- Add nonlinear corrections that adequately represent the key nonlinear effects.
- Formulate the problem based on a main linear block and nonlinear feedback loops.
- Perform simulations in a way that takes advantage of this formulation.
- Verify/update the models by comparisons with selected tests and/or high-fidelity solutions of rigid and elastic vehicles.
- IOM research at Technion resulted in two “plug-and-play” software packages for various IOM applications:
  - Matlab/Simulink code with time-domain models
  - The DYNRESP code with frequency-domain models
Presentation Outline

- The DYNRESP code for dynamic response and loads
- Control nonlinearities:
  - Case 1: Gust response with nonlinear control system
- Structural nonlinearities:
  - Case 2: Actuator free play
  - Case 3: Solid fins with nonlinear plates
- Aerodynamic nonlinearities:
  - Case 4: Discrete gust loads
Dynamic Response with Nonlinear Control, Motivation

- A400M is a military cargo aircraft currently in flight tests by Airbus Military (formerly EADS-CASA).
- Dynamic gust, landing and maneuver loads provide critical design cases.
- Symmetrically actuated ailerons and wide-band actuators facilitate maneuver and gust loads alleviation.
- Control limits, activation zones and operation logics introduce important nonlinear effects.
- The new DYNRESP code was developed for Airbust Military based on lessons learned in the A400M project.
DYNRESP Main Objectives

- Coverage of all aspects of aircraft dynamic loads analysis
- Efficient massive computations in industrial environment
- Robustness
- Advanced analysis capabilities and functionality
- Flexibility is adding new features and non-linear effects
- User friendliness
- Being based on data from commonly used structural, multi-body, aerodynamic and control software packages.
- Compatibility with typical in-house loads codes.
- Applicability with a variety of computational platforms.
Dynamic Response and Loads Disciplines

• Modal and control-surface response to:
  – deterministic gusts
  – pilot commands
  – direct forces.

• Response simulations are used in subsequent calculations of

<table>
<thead>
<tr>
<th>Short signals:</th>
<th>Long signals:</th>
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<tbody>
<tr>
<td>discrete gust loads</td>
<td>continuous gust loads</td>
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<tr>
<td>maneuver loads</td>
<td>actuator oscillatory failure</td>
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<td>store ejection</td>
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<td>coupling</td>
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<td>landing loads</td>
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Basic Formulation

• Second-order frequency-domain equations of motion of the main linear block.
• FFT/IFFT techniques
• Treatment of zero-frequency singularities
• Enforcement of zero initial displacements and loads
• Segmentation of long excitation signals.
• Unified implementation to all loads disciplines.
• The system may include any combination of nonlinear and isolated-linear control blocks
• Direct-force feedback may be added for nonlinear aerodynamic effects.
**DYNRESP General Flow Chart**

- **Data:**
  - Input parameters as in NASTRAN/ZAERO
  - Data matrices from NASTRAN
  - Data matrices from ZAERO

- **Simulations:**
  - Discrete gusts / Maneuver commands / Direct forces
  - Control on/off / Control on/off / Air on/off

- **Modal response:**
  - Modal and control surface displacements, velocities, accelerations.
  - Time and frequency domain

- **Loads:**
  - Summation of Forces or Mode-Displacement method
  - Grid-point forces, aero pressures, section loads
Time-Domain Gust Response with Nonlinear Control

- TD state-space ASE models based on rational-function approximation of the aerodynamic coefficient matrices.
- Export the TD model to simulation codes such as Matlab/Simulink.
- Dynamic response with nonlinear control system.
- Use resulting modal response $\{\xi(t)\}$ and actuator outputs $\{\delta(t)\}$ for loads analysis.
FD-Convolution Gust Response with Nonlinear Control

- **Stage 1**: FD response of the main linear block to gusts and control commands with the nonlinear block disconnected.
- **Stage 2**: TD response of the linear block to gust and to unit impulses from the nonlinear block using FFT techniques.
- **Stage 3**: Adding nonlinear effects based on nonlinear models and convolution with impulse responses.
Case 1: Gust loads on Generic Transport Aircraft (GTA) model with nonlinear control

with H. Climent and C. Maderule and L. Anguita of Airbus Military,

- Structural and aerodynamic models

- Control system: symmetrically activated ailerons based on accelerometer near CG

- Frequency: 5 Hz.
Nonlinear control system

- TF1: basic linear control law
- NL1: Cluster of nonlinear elements. Main features:
  - limit the deflections and rates
  - hold peak deflections
  - minimal deflection 1°
- TF2: enforces slow decay
- NL2: selection switch
Modal response

- FD-convolution vs. TD-Simulink
- FD signals return to zero at $T=8.192 \text{ sec}$
- Differences in rigid-body response (Modes 1, 2) do not affect loads.
- Elastic responses practically identical.
Actuator response, linear and nonlinear FCS
Modal response in the open- and closed-loop cases
DYNRESP as Framework for the IOM Approach

- The presented loads process with TD or FD models supplemented with nonlinear control feedback loops can serve as a framework for IOM applications.
- Natural extension of common analysis and design practices.
- The linear response is based on user’s models.
- Very efficient.
- Depends of course on the ability to model the nonlinearity by adequately accurate feedback loops.
Case 2: LCO Simulations with actuator free play with Paul Gold

- A common strong nonlinearity that is also difficult to model is free play in the actuator connections to the control surfaces.

- Aileron in the free-play zone: out of the free-play zone:
Free-play IOM Block Diagram
Main Modeling Difficulties and Solutions

• Efficient models are based on a single set of normal modes
  – **Problem**: How to represent large local concentrated forces during time simulations?
  – **Solution**: Use local *fictitious masses*.

• Free-play causes asymmetric response.
  – **Problem**: Do we have to use full-aircraft models?
  – **Solution**: No, we can use symmetric and antisymmetric modes with *modal coupling effects*. 
Demonstration UAV Model

Structural finite-element model
Aerodynamic panel model
Structural Model with Fictitious Masses

- Eigenvalue problem with nominal structure and fictitious masses:
  \[
  [K_{aa}][\phi_{ai}] = [M_{aa} + M_F][\phi_{ai}][\Omega_i]
  \]
  - In our case: \(\delta_s\) is aileron elastic rotation relative to wing
  - actuator stiffness \(k_\theta=0\); fictitious mass \(m_F=100Kgm^2\)
  - “Cleaning” the generalized mass matrix:
    \[
    [\tilde{M}_{ii}] = [M_{ii}] - [\phi_{ai}]^T [M_F] [\phi_{ai}]
    \]
  - Adding actuator stiffness:
    \[
    [\tilde{K}_{ii}] = [K_{ii}] + [\phi_{ai}]^T [\Delta K] [\phi_{ai}]
    \]
  - Eigenvalue problem for actual natural frequencies:
    \[
    [\tilde{K}_{ii}][\psi] = [\tilde{M}_{ii}][\psi][\Omega_h]
    \]
  - Mode shapes of actual structure:
    \[
    [\phi_{ah}] = [\phi_{ai}][\psi]
    \]
## Natural frequencies based on FM model

\[ k_\mu = 0.001 \left[ \frac{kg m^2}{sec^2} \right] \quad k_\mu = 30 \left[ \frac{kg m^2}{sec^2} \right] \]

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Linear open-loop model with floating ailerons

- Use FM-cleaned modes with \( k_\theta = 0 \).
- State-space aeroelastic equations of motion:
  \[
  \{ \dot{x}_{ae} \} = [A_{ae}] \{ x_{ae} \}
  \]

where

\[
\begin{align*}
\{ x_{ae} \} &= \begin{pmatrix} \xi \\ \dot{\xi} \\ x_a \end{pmatrix}, \\
[A_{ae}] &= \begin{bmatrix} 0 & I & 0 \\ -[\bar{M}]^{-1} [K_{hh} + qA_0] & -[\bar{M}]^{-1} \left( B_{hh} + \frac{qL}{V} A_1 \right) & -q[\bar{M}]^{-1} [D] \\ 0 & [E] & \frac{V}{L} [R] \end{bmatrix}, \\
[\bar{M}] &= [M_{hh}] + \frac{qL^2}{V^2} [A_2]
\end{align*}
\]

- The aerodynamic coefficient matrices are of the rational function
  \[
  \left[ \tilde{Q}_{hh}(ik) \right] = [A_0] + [A_1] ik + [A_2] (ik)^2 + [D] (ik[I] - [R])^{-1} [E] ik
  \]
  that approximates the tabulated generalized aerodynamic matrices \([Q_{hh}(ik)]\)
Linear open-loop model with nominal actuators

- State-space aeroelastic equations of motion

\[ \begin{align*}
\{ \dot{x}_{ae} \} &= \left[ A_{ae} \right] \{ x_{ae} \} + \left[ B_{ae} \right] \{ M_{inp} \} \\
\text{where } & \quad [B_{ae}] = \begin{bmatrix}
0 \\
\bar{M}^{-1} [\phi_{sh}]^T \\
0
\end{bmatrix}
\end{align*} \]

where \([\phi_{sh}]\) is the row partition of \([\phi_{ah}]\) associated with \(\{ M_{inp} \}\).

- Structural rotations of the control surfaces:

\[ \{ \delta_s(t) \} = [\phi_{sh}] \{ \xi(t) \} \]

- Actuator forces are introduced by the feedback loop:

\[ M_{inp_i} = k_{\theta_i} \delta_{s_i} \]

- Can perform nominal flutter analysis with closed actuator loop.
Nonlinear open-loop model with free play

- The system is driven by actuator outputs \( \{ \delta_c \} \)
- The elastic aileron deflections become
  \[
  \{ \delta_s (t) \} = \{ \delta_a (t) \} - \{ \delta_c (t) \}
  \]
  where \( \{ \delta_a (t) \} \) is the vector of actual aileron deflections
  \[
  \{ \delta_a (t) \} = [\phi_{sh}] \{ \xi (t) \}
  \]
- The linear plant model is constructed with symmetric and antisymmetric modes, yet uncoupled.
- Right and left aileron output deflections:
  \[
  \begin{pmatrix}
  \delta_{s_r} \\
  \delta_{s_l}
  \end{pmatrix} =
  \begin{bmatrix}
  \phi_{sh_s} & \phi_{sh_a} \\
  \phi_{sh_s} & -\phi_{sh_a}
  \end{bmatrix}
  \begin{pmatrix}
  \xi_s \\
  \xi_a
  \end{pmatrix} -
  \begin{pmatrix}
  \delta_{c_r} \\
  \delta_{c_l}
  \end{pmatrix}
  \]
- Right actuator input moment with free play \( \pm \delta_{f_r} \):
  \[
  M_r =
  \begin{cases}
  -k_\theta (\delta_{s_r} + \delta_{f_r}) / 2 & \text{if } \delta_{s_r} < -\delta_{f_r} \\
  0 & \text{if } -\delta_{f_r} \leq \delta_{s_r} \leq \delta_{f_r} \\
  -k_\theta (\delta_{s_r} - \delta_{f_r}) / 2 & \text{if } \delta_{s_r} > \delta_{f_r}
  \end{cases}
  \]
- Left aileron moment \( M_l \) is determined similarly.
Asymmetric LCO in response to unit aileron command

- The linear ASE plant, with the nonlinear feedback loop was implemented in Simulink.
- Simulations performed for deviations from the steady level flight.
- The right and left aileron elastic rotations $\delta_{s_r}$ and $\delta_{s_l}$ were calculated relative to the initial $\delta_t = -1.02^\circ$.
- A roll simulation was performed for response to an antisymmetric step actuator command $\delta_c = 3.67^\circ$ that brings the right aileron to the middle of the free play zone.
- The right aileron experiences almost harmonic LCO at 5 Hz.
Elastic rotations of right and left ailerons, unit command

Right:

Left:
The nonlinear ASE model is augmented with a 3rd-order actuator and a classical proportional-integral (PI) roll controller. The PI controller was designed to yield acceptable closed loop stability margins for the no-free-play case.

Time histories of system response with no free play case:

**roll rate:**

**roll-rate error:**
Closed loop response, with actuator free play

Actual and commanded aileron rotations:

Elastic aileron rotations, roll rate and roll-rate error:
Closed-loop response with actuator free play in typical roll maneuver sequence

Actual and commanded aileron rotations:

Elastic aileron rotations, roll rate and roll-rate error:
Case 3: Solid fin with nonlinear plate elements with Dani Levin

Steel Fin
0.9 mm thickness
Basic equation of motion

\[
[m] \{\ddot{u}\} + [c] \{\dot{u}\} + [k] \{u\} = \{F_A(t)\}
\]

Structural Part

Stiffness matrix changes due to stress stiffening

Unsteady aerodynamic forces
Nonlinear in-plane strain

\[ \varepsilon = \begin{bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \\ -\frac{\partial^2 w}{\partial x^2} \\ -\frac{\partial^2 w}{\partial y^2} \\ 2\frac{\partial^2 w}{\partial x \partial y} \end{bmatrix} + \begin{bmatrix} \frac{1}{2} \left( \frac{\partial w}{\partial x} \right)^2 \\ \frac{1}{2} \left( \frac{\partial w}{\partial y} \right)^2 \\ \left( \frac{\partial w}{\partial x} \right) \left( \frac{\partial w}{\partial y} \right) \\ 0 \\ 0 \\ 0 \end{bmatrix} = \left\{ \varepsilon_0^{pl}, \varepsilon_0^b \right\} + \varepsilon_{NL}^{pl} \]

- Von Karman equations are used.
- Nonlinear strain part is added due to stretching of the plate in bending.
Co-Rotational Approach (2)

\[
\begin{align*}
\{ \delta^e_b \} &= \{ \delta^e_b \}_{\text{Rigid}} + \{ \delta^e_b \}_{\text{Elastic}}
\end{align*}
\]
IOM Time-Domain Formulation

- Minimum-state rational approximation of the unsteady aerodynamic force coefficient matrices, using ZAERO, yields:

\[
\begin{bmatrix}
    \dot{\xi} \\
    \ddot{\xi} \\
    \dot{x}_a
\end{bmatrix} =
\begin{bmatrix}
    0 & I & 0 \\
    -[\bar{M}]^{-1} [K_L + q_\infty A_0] & -[\bar{M}]^{-1} \left[ \frac{q_\infty L}{V} A_1 \right] & -q_\infty [\bar{M}]^{-1} [D] \\
    0 & [E] & \frac{V}{L}[R]
\end{bmatrix}
\begin{bmatrix}
    \xi \\
    \dot{\xi} \\
    x_a
\end{bmatrix} =
\begin{bmatrix}
    0 \\
    [M]^{-1} [\Delta K(\xi)] \\
    0
\end{bmatrix}
\begin{bmatrix}
    \xi \\
\end{bmatrix}
\]

\[
[M] = [M] + \frac{q_\infty L^2}{V^2} [A_2]
\]
IOM block diagram
Static Loading Comparison

- Static loads with no aerodynamics:  
  \[
  \left( [K_L] + [\Delta K(\xi)] \right) \{\xi\} = \{F_{\text{ext}}\}
  \]

- Tip displacements:

- 4 modes are sufficient
Linear Flutter Analysis

v-g Plot for Cropped Delta Wing, $M=0.85$

Torsion-Bending flutter mechanism at:
$M=0.85$, $q=18.96\text{kPa}$
$\omega_f=45.6\text{ Hz}$
Linear System Time Simulation

Deflection vs Time, node 12

Pitch Angle vs Time, node 12

Node 12 displacement and rotation at:

q=19.8kPa
Nonlinear Time Simulation

Deflection vs Time, node 12

Pitch Angle vs Time, node 12

Deflection vs Time, node 32

Pitch Angle vs Time, node 32

q=19.16kPa

q=21.72kPa

q=23.92kPa
Comparison with wind-tunnel test and other works

Results Comparison, Node 12 Deflection

Results Comparison, LCO Frequency
Cases 4: Gust Response with Nonlinear aerodynamics
with Daniella Raveh and Alex Shousterman

- MSC/NASTRAN structural model, ZAERO aero model and EZNSS Euler surface grid of generic transport aircraft:
CFD Response Simulations at Mach 0.85

- Wing lift coefficient vs. AOA, CFD and linear models, rigid aircraft.
- Nonlinear aerodynamic effects may yield reduced gust loads in practical design cases.

![Graph showing C_L vs. Angle of Attack]
Distribution of lift and moment coefficients over the wing
Distribution of pressure coefficients over the wing

EZNSS

ZAERO
Distribution of lift coefficients over the wing
Distribution of $X_{cp}$ over the wing
Linear correction factors in ZAERO aerodynamics

- Linearly distributed correction factors to yield linear $C_l$ and $C_m$ of aerodynamic strips:

  Wing factors
  
  horizontal tail factors
DYNRESP gust response with non-linear feedback

• Linear $C_l$ and $C_m$ of the nominal model are “sensors”
• Non-linear feedback elements are based on look-up tables from CFD
• $C_l$ and $C_m$ corrections are introduced by direct forces and moments at the wing and tail main spars.
• DYNRESP calculated 2 cases:
  – Linear correction with linear look-up tables
  – Non-linear correction with nonlinear look-up tables
Wing-root bending moment response to 1-cos discrete
Wing lift coefficient due to sharp-edge gust, 0 to 4°
Wing lift coefficient due to 1-cos discrete gust, up to 4°