Finite Element Analysis Techniques for Aircraft Design Applications

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Aaron Latty, BSME MSc
Sales and Support Manager
Strand7 UK Limited

Making finite element analysis easier
Aaron Latty

- Started in aerospace industry 1996
- Structural design of airframes, wings, undercarriage
- MSc in Computational and Software Techniques in Engineering - 2003
- Conceptual design research on high speed marine craft, hovercraft, seaplanes
- Joined Strand7 in 2008, specializing in finite element analysis
Strand7 Pty Ltd

- Established in 1988
- Head Office: Sydney Australia
- Primary activity: Research and Development of Finite Element Analysis Software
- Product: **Strand7 FEA Software**
- Support to Strand7 users
- FEA Consultancy
Content of Presentation

• Finite Element Analysis (FEA) Overview
• Wing-in-ground Effect Craft – Global Strength Analysis
• Atmospheric Research Craft – Fairing Study
• Cessna 172 - Global Loads Model
• Questions
The Finite Element Method (FEM) is a numerical technique for solving *field problems* such as:

- Elasticity problems (i.e. stress analysis)
- Heat transfer
- Fluid dynamics
- Acoustics
- Magnetics
- … and many others
FEA – Overview

• It involves the following steps:
  – Dividing the domain (i.e. a structure) into a number of very small regions (the elements)
  – Making an assumption about how the field variable can vary over a single element (i.e. constant stress, linear stress, etc.)
  – Assembling a matrix that accounts for the interaction between the elements (interaction is at the nodes)
  – Solving the matrix to determine the overall response (e.g. response to applied loads)
Elements

• Different types of elements can be formulated, and for structural analysis they can be broadly classified as:
  – Beam (or line) elements
  – Plate/shell (surface) elements
  – Brick (solid) elements
Beams for frameworks
Plates for a detailed wing
Bricks for thick solids
Stages in Practical FEA

Think about the problem before you start…
That is…

• Classify the problem
  – Linear/nonlinear
  – Static/dynamic
  – What results are needed?
• What do you wish to learn?
• Decide what is important and what is not.
• Can the analysis be done by hand?
If FEA is the way to go, then embark on the three stages of practical FEA...

1. Define the problem.
2. Determine the response.
3. Interpret the results (design).
Pre-processing

• Planning
  – Goal is to capture the appropriate detail to allow understanding of the problem
  – Decide how to consider the applied loads and boundary conditions
  – Is the material to be treated as homogeneous, isotropic and linear elastic?
  – Can the analysis be simplified to 2D (e.g. plane strain, plane stress) or is 3D needed?
  – Can symmetry be exploited?
Pre-processing

• Modelling
  – Define geometry (e.g. CAD or otherwise)
  – Generate the mesh (automatic or manual)
  – Define material properties
  – Apply boundary conditions (restraints)
  – Apply loads (forces, acceleration, thermal,…)
  – Verify that what you have modelled is what you intended (not always easy!)
Mesh density

• Increasing level of discretization for a circular tube
  – What is the appropriate level?
Example

• Stress concentration in a thin sheet of aluminium with a circular hole and uniform far-field stress
  – Three levels of mesh refinement using simple elements, produce three different results (but hopefully convergent)

• In other words, correct meshing and element choice is very important.
Solving

• While pre-processing is generally a very interactive task, solving usually is not.
• The solver takes over to assemble a stiffness matrix from the mesh and proceed to solve for the field variable.
• In a structural FEA, the field variable is displacement (and rotation) at the nodes.
• Once the displacement field is calculated, other results such as stress, force, etc., are calculated.
Solving

• For a linear problem, it’s basically the solution of Hooke’s Law
  – 1D: \( F = K \times X \) – just like a spring

  \[
  K \quad \rightarrow \quad F
  \]

  \[
  K \quad \rightarrow \quad F
  \]

  \[
  X
  \]

  – 2D and 3D: \( \{F\} = [K]\{X\} \)
    • \( \{F\} \) is a vector, \([K]\) is a matrix and \(\{X\}\) is a vector
Solving

• For non-linear problems, things are generally more complicated
  – K can be a function of X (i.e. lateral stiffness of a cable is a function of the axial strain in the cable)
    i.e. \( \{F\} = [K(X)]*\{X\} \)
    • We need X to find K, but we need K to find X !
    • Except for some simple cases, this requires an iterative solution procedure
Post-processing

- Check solver logs
- Interpret results
  - Numerous data are generated
    - Displacements
    - Strains
    - Stresses
    - etc.
  - These can be displayed in various ways
    - Contour plots
    - Vector plots
    - Graphs
    - Tabular listings
Be aware of the assumptions!

- Assumptions must be understood
  - If you use an element that can support only a linear displacement field, then a single element can be used to model a constant stress field:
    - Stress = E * strain
    - (Engineering) strain is the first derivative of displacement, hence linear displacement gives constant strain.
  - If the stress field is not constant, you can:
    - Use more linear elements (modelling a non-linear result as piecewise linear), or
    - Use a higher-order elements (e.g. quadratic) if your FEA program offers them.
Be aware of the assumptions!

• Some are built in by the software developer
  – It is important to be fully aware of the assumptions and limitations that are built into the software
  – A good FEA system will have
    • A comprehensive **Theoretical Manual** so that you can review and understand the inherent assumptions and limitations of the software and/or its implementation, and
    • A detailed **Verification Manual** that clearly documents the results that you can expect under different situations (access to the files used to produce these results is a definite advantage)
FEA in Aircraft Design

- Aircraft Modifications
- Loads Analysis
- Modal Analysis
- Deflection analysis
- Configuration checks
Wing-in-ground Effect Craft
Global Strength Analysis
Flightship – Mesh Definition

CAD Geometry

Final Mesh
Flightship – Loads

- Landing on the Nose
- Landing on the Step
- Landing on the Tail with Sponson Loads
- Landing on the Tail without Sponson Loads
- In-flight Sponson Strike
- Aerodynamic Wing Lift
- Applied as per FAR Part 23
Flightship - Results

• Global behaviour was captured including
  – Displacements
  – Plate forces
  – Ply strains and reserve factors

• Laminate results were evaluated at each ply over an envelope of all load cases
Flightship - Results
Fairing Study

BAe 146-301
Fairing Study

Fairing on Radiometer Blister

Analysis performed by Cranfield Aerospace on behalf of Facility for Airborne Atmospheric Measurements
Fairing - Modelling
Fairing - Loads

- Fairing loads were determined using wind tunnel testing
- 18 tappings
- Aircraft angles of attack ranging from 6 to 16 degrees
- Cp data was provided for upper, side and lower surfaces for all angles with and without the cover
Fairing - Results

• Both configurations were analyzed using the same model

• Results were determined for all plies for all load cases
Loads Model Example
Cessna 172

Photograph courtesy of Cessna Aircraft Company
Loads Model Example
Cessna 172

• Free-floating structures, like complete aircraft, can be difficult to model using standard FEA programs
• The ability to perform an *Inertia Relief* analysis greatly simplifies the task
Inertia Relief

Simple example – steady straight and level flight
  – Lift = Weight (Thrust = Drag)

• Apply the pressure distribution representing lift
• Apply -1g vertical acceleration to balance the lift

Load application should be simple enough, but the problem is that there are no restraints.
Inertia Relief

Not so simple example – a manoeuvre

- Apply the pressure distribution over the aircraft – this gives an applied force vector \{F\}
- Determine accelerations required to balance this load
Inertia Relief

• If the CG of the aircraft is at the origin, the linear accelerations are easily determined (F=Ma).

• For the angular accelerations, we need to find the rotational inertia of the aircraft and solve for the angular accelerations to balance the external moments Mx, My, Mz.

\[
\begin{bmatrix}
I_{xx} & -I_{xy} & -I_{xz} \\
-I_{xy} & I_{yy} & -I_{yz} \\
-I_{xz} & -I_{yz} & I_{zz}
\end{bmatrix}
\begin{bmatrix}
\ddot{x} \\
\ddot{y} \\
\ddot{z}
\end{bmatrix} =
\begin{bmatrix}
M_x \\
M_y \\
M_z
\end{bmatrix}
\]
Loads Model Example
Cessna 172
Loads Model Example
Cessna 172

<table>
<thead>
<tr>
<th>MIN (N.m)</th>
<th>MAX (N.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.568980x10^3</td>
<td>2.674500x10^3</td>
</tr>
</tbody>
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[Diagram of Loads Model Example for Cessna 172]
Loads Model Example
Cessna 172

4: Combination Case [Combination 1] (-70,0,56)
4: Combination Case [Combination 1] (-70,0,56)
Questions