VABS-IDE: VABS-Enabled Integrated Design Environment (IDE) for Efficient High-Fidelity Composite Rotor Blade and Wing Section Design

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Objective

Army SBIR (A08-022): To develop a means to rapidly assess aeromechanics issues for rotorcraft configurations with realistic rotor and wing structural properties during the conceptual design stage

- Specifically, a design tool is needed that can provide realistic engineering beam properties for blades and wings given basic aircraft geometries, applied load distribution and design constraints.
- The realistic properties should satisfy structural design requirements such as static and fatigue stress, ballistic tolerance and dynamic stability guidelines.
- Variables should include material properties and cross-section topology.
VABS Concept

3D Anisotropic Continuum Mechanics

Reformulate the Kinematics Using DRT

Dimensional Reduction Using VAM

2D Cross-Sectional Analysis

Constitutive Models

Recovery Relations

3D Behavior

1D Beam Analysis (Geometrically Exact)

Global behavior (linear/nonlinear)
Why VABS?

Material properties and dimensions

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{11}$</td>
<td>$18.73 \times 10^6$ psi</td>
</tr>
<tr>
<td>$E_{22}$</td>
<td>$1.364 \times 10^6$ psi ($= E_{33}$)</td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>$0.7479 \times 10^6$ psi</td>
</tr>
<tr>
<td>$G_{13}$</td>
<td>$0.6242 \times 10^6$ psi</td>
</tr>
<tr>
<td>$G_{23}$</td>
<td>$0.3686 \times 10^6$ psi</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>0.3 ($= \nu_{13} = \nu_{23}$)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$1.450 \times 10^{-4}$ lb.sec²/in.⁴</td>
</tr>
<tr>
<td>Width</td>
<td>0.5 in.</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.125 in.</td>
</tr>
<tr>
<td>Length</td>
<td>7.5 in.</td>
</tr>
</tbody>
</table>

Generalized Timoshenko model

<table>
<thead>
<tr>
<th>Stiffness</th>
<th>VABS Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{11}$</td>
<td>$0.3566 \times 10^6$ (lb)</td>
</tr>
<tr>
<td>$S_{12}$</td>
<td>$0.1274 \times 10^6$ (lb)</td>
</tr>
<tr>
<td>$S_{22}$</td>
<td>$0.1005 \times 10^6$ (lb)</td>
</tr>
<tr>
<td>$S_{33}$</td>
<td>$0.8634 \times 10^4$ (lb)</td>
</tr>
<tr>
<td>$S_{44}$</td>
<td>$0.5069 \times 10^3$ (lb-in²)</td>
</tr>
<tr>
<td>$S_{45}$</td>
<td>$-0.3215 \times 10^3$ (lb-in²)</td>
</tr>
<tr>
<td>$S_{55}$</td>
<td>$0.4578 \times 10^3$ (lb-in²)</td>
</tr>
<tr>
<td>$S_{66}$</td>
<td>$0.4062 \times 10^4$ (lb-in²)</td>
</tr>
</tbody>
</table>

VABS sectional inertia properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>$0.9063 \times 10^{-5}$ lb.sec²/in.²</td>
</tr>
<tr>
<td>$i_2$</td>
<td>$0.1180 \times 10^{-7}$ lb.sec²</td>
</tr>
<tr>
<td>$i_3$</td>
<td>$0.1888 \times 10^{-6}$ lb.sec²</td>
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</table>
Why VABS?

Natural frequencies (Hz)

<table>
<thead>
<tr>
<th>Mode</th>
<th>VABS</th>
<th>3D</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>332.5</td>
<td>333.8</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>905.2</td>
<td>919.0</td>
<td>1.5</td>
</tr>
<tr>
<td>3</td>
<td>1317.9</td>
<td>1321.4</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>1737.1</td>
<td>1792.6</td>
<td>3.1</td>
</tr>
<tr>
<td>5</td>
<td>2807.4</td>
<td>2956.9</td>
<td>5.1</td>
</tr>
<tr>
<td>6</td>
<td>3349.4</td>
<td>3357.1</td>
<td>0.3</td>
</tr>
<tr>
<td>7</td>
<td>3522.6</td>
<td>3560.1</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Why VABS?

The 4th mode using 3D FEA

- 3D FEA
  - 29673 DOFs, 92 seconds
- Efficient high-fidelity modeling
  - VABS: 1053 DOFs, ~0.1 seconds
  - 1D solution: 240DOFs, ~1 second

The 4th mode using VABS
Why VABS?

Cantilever composite rectangular beam:

- **Layup:** $[(-45/ + 45/0/90)10]_s$
- $b=0.25\text{ in.}, h=1\text{ in.}, L=5\text{ in.}$
- Shear force applied at the tip:
- ANSYS 3D FEA uses 25,600 brick elements, takes about one hour in a PC.
- VABS (640 quadrilateral elements) less than 0.5 second, the 1D solution can be obtained by hand.
Transverse shear stress $\tau_{13}$ at mid-span and $x_2 = 0$
Transverse shear stress $\tau_{12}$ at mid-span and $x_2 = 0$
Why VABS?

Predictions of VABS and other analysis software for multi-layered composite pipe

SVBT: Saint Venant Beam Theory

% differences calculated with respect to SVBT
What VABS Can Do for You?

- **VABS** takes a finite element mesh of the sectional geometry and material as inputs to calculate sectional properties, which are needed for beam analysis code. VABS can also recover 3D displacements/strains/stresses over the section: a link between 3D and 1D.

- **VABS** can be used independently for **structural design of wing sections** (topology and material): e.g., maximize the torsional stiffness while maintaining the desired mass or minimize the difference between the aerodynamic center and elastic axis.

- **VABS** provides high-fidelity information of composites with no additional computing cost to the 1D beam analysis.
VABS-enabled IDE Configuration

IDE VABS

- CAD/PreVABS
  - Geometry modeling
    - Material Parameter
      - FE Mesh
  - Stiffness Matrix
    - Stress/Strain Recovery
    - Material Parameter

- VABS
  - Stiffness Matrix

- Optimizer
  - Blade shape
    - Blade Size
      - Material Parameter
  - Stiffness Matrix

- PostProcessor
  - Stress/Strain Recovery
    - Optimization Result
CAD Environment

2D Cross Section → Section Shape → Section Size → Automation → Material description → PreVABS
Material Database

Key: Each part can be assigned with different material parameters.

- Create
- Show
- Modify
- Delete
PreVABS

- PreVABS prepares mesh and input file for VABS
- PreVABS interprets the geometry and materials properties from CAD
- PreVABS deals with arbitrary realistic cross-sectional shapes
Modify VABS for Integration

- **Error handling**: instead of terminating the code when critical errors arise (and output error messages are sent to the screen), the code has been modified so that, when critical errors encountered, VABS returns control to the calling program, along with corresponding error messages.
- **Memory allocation/de-allocation** are carefully handled to avoid memory leak due to multiple runs.
- **I/O**: all the inputs/outputs are localized at the I/O processing subroutines to facilitate connection with other codes.
- **True “play-n-plug” capability**: analysis capabilities encapsulated in dynamic link libraries (DLLs), which can be integrated with virtually any environment.
- **True cross-platform capability**: same source codes and same make files for all platforms including Windows/Mac/Linux/Unix
- **Highly optimized**: For a realistic cross-section with 200,000 degrees of freedom, generalized Timoshenko modeling takes 83 seconds on a Dell laptop, much faster than previous versions and other implementations of VABS.
Modify VABS for Integration

- **VABS 3.3** is the latest version of VABS that integrated several of these advancements:
  - Improved input format that reduces size of input file by ~75%
  - Error handling, memory management, I/O advancements, dynamic link libraries for better integration with other codes
  - Improved efficiency: for realistic blade sections of ~200,000 DOF, VABS 3.0 runs for 58 seconds compared with VABS 2.1.1 ~7.5 minutes
  - A limited capability freeware version for users to test VABS capabilities simple problems

- **VABS-AD**: A modified version of VABS 3.3 that provides accurate sensitivities of VABS results with respect to key variables. These sensitivities will replace conventional gradient calculations in gradient-based optimization
Robust Optimizer for IDE

Minimize user-specified objective function:
- Material cost
- Weight

Given user-specified constraints:
- Geometric
- Frequency Placement
- Safety (autorotational capability, maximum stresses)
- Manufacturing constraints

Resulting Layup Information:
- Shear web location, skin and spar thicknesses
- Materials used and stacking sequence for each component
Iterative Two Stages of Optimization

Global: 1-D Beam Optimization
Input: User specified objective function
Design Space: Sectional stiffnesses and mass, outer geometry
Purpose: Minimize Objective Function
Constraints: Natural Frequencies, autorotational inertia

Local: VABS Optimization
Input: Sectional stiffnesses and masses from global process
Design Space: Layup properties: # of plies, layup direction and materials
Purpose: Find layup that achieves specified sectional properties
Constraints: Manufacturing constraints, maximum stresses
Postprocessor

The postprocessor should be able to visualize

1) the geometry modeling;
2) the meshing of the triangular and quadrilateral elements;
3) section deformation, and stress and strain distribution over the local section, in both the user coordinate system and the material coordinate system; and
4) the data through line or surface plots, such as design objectives versus design variables, or stress distribution along a certain direction or on a surface.
5) Optimization results and iteration information
VABS IDE 2.0

Advanced Dynamics Inc

2010
The CAD module can create points, curves and surfaces to form blade section or import models created by other CAD software.
Material Database

Can be manually keyed in or imported from data files
PreVABS: Generating FE Model for VABS
Postprocessor
Conclusions

- A versatile, ambitious Integrated Design Environment (IDE) with VABS as the analysis engine is being developed with a commercial quality GUI.
- The IDE has the all functionality necessary for structural design of blade or wing sections:
  - Commercial quality CAD: creating or import sectional geometry
  - PreVABS: creating the finite element model with maximum automation
  - Enhanced VABS: true “play-n-plug” capability; true cross-platform capability; highly optimized
  - Robust optimizer: automatically seeks the optimal section satisfying constraints
  - Postprocessor: To visualize both analysis and optimization results
Acknowledgment

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