Identification problems in structural dynamics

Presented By: Giuliano Coppotelli

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SUMMARY

- **Structural updating of the VEGA-UCMEC FE Model Using Vibration test data**
  - Developments of structural updating procedures
    - Base formulation
    - Rank Control Enhancement

- **Model Updating of an UAV Aeroelastic System Based on Ground and In-Flight Test Data**
  - Developments of Operational Modal Analysis Methods
    - Assessment of Time- and Frequency-Domain Techniques
    - Aeroelastic Identification

- **Concluding remarks**
Identification problems in structural dynamics

STRUCTURAL UPDATING OF THE VEGA-UCMEC FE MODEL USING VIBRATION TEST DATA

G. Coppotelli, R. Rinaldi, V. Spadoni,
AIM: Improvement of a sensitivity-based updating procedure for very large size FEM

Numerical Analysis

Experimental Investigation

K, M

Response Model

F.E. Model

Updating

Sinus Vibration Tests

Vibration control

Health Monitoring

Qualification and Prototype Tests

Aeroelastic analyses

Fatigue-life analyses

VEGA-UCMEC
Motivations

- Higher and higher accuracy in predicting dynamic behavior of structures required by aerospace industries
  - better performances
  - lighter structures

- Development of methods for correlation (analysis/test) and updating of FE model
  - Unavoidable geometrical simplifications and/or element modeling errors
  - Actual in B.C., uncertainties in the geometrical/mechanical properties
  - Estimation process adopted to derive the experimental dynamic model
Additional difficulties arise when dealing with very large FEM:

- High number of design parameters
- Reduction of accuracy
- Non-unique updated physical model

Updating procedure based on the minimization of an error function of design variables associated to the F.E. model:

- Use of sensitivity of correlation functions of the TFs, to design parameters
- Ill-conditioned sensitivity matrix
The VEGA Launch Vehicle

- Axis symmetric body
  - Weight at launch w/o payload: 137 tons
  - Overall height: more 30 m
  - Diameters:
    - 3m at the base
    - 2m at the middle section
    - 2.6m at P/L Fairing

UCMEC - Upper Composite Mechanical Configuration

Payload Composite

AVUM & IS34

Z9 SRM

Z23 SRM

IS 23

P80 SRM

IS 12

IS 01
The VEGA Launch Vehicle

Objectives of the UCMEC Sine Vibration Test

- To verify structural functionality at flight expected levels with a qualification (1.25) factor.
- To demonstrate the validity of the VEGA LV Upper Composite design (4th stage, adapter, P/L dummy and Fairing Boat-tail).
Updating of VEGA UCMEC FEM

- Sinus Vibration Tests
  - 350 acceleration channels
  - Excitation in three orthogonal directions

- The most severe transfer functions measured in the LV axial direction
  - 72 TF included in the updating process
Updating of VEGA UCMEC FEM

- FEM characterized by
  - 1,500,000 Dofs
  - 250,000 elements

- Transfer functions from MSC.NASTRAN enforced motion
Identification problems in structural dynamics

MODEL UPDATING OF AN UAV AEROELASTIC SYSTEM BASED ON GROUND AND IN-FLIGHT TEST DATA

L. Balis Crema, F. Mastroddi, E. Schiavoni, G. Coppotelli
**AIM:** Improvement of a sensitivity-based updating procedure for very large size FEM

Identification of **aeroelastic systems** and **Generalized Aerodynamic Force** matrix (GAF) through *GVT* and *Flight Tests*

**APPROACH**
- **Aeroelastic system** synthesized using Operational Data from flight tests
- **GAF** matrix from both ground (structure) and in-flight tests (aeroelasticity)

**REQUIREMENT**
- • **Updated structural model**

**In-Flight Tests:**
- Aeroelastic modes and poles

**Ground Vibration Tests:**
- Structural modes, frequencies and $\zeta$

**Method for FRF synthesis**

**Aeroelastic FRF**

**GAF Matrix**
Main Activities

Aeroelastic System and GAF synthesis

Numerical simulation (MSC nastran)
- FEM Tuning
- Modal Analysis
- Aeroelastic Analysis

Experimental Tests
- In-Flight: Output only
- On-Ground: Input output
Recent Output-Only developments have enabled new approaches for the modal parameters estimation

- Only the natural responses of the structure are needed
- The input is not required
  
  **Cost reduction**

- Actual external loading and boundary condition
  
  **Accurate dynamic identification**

This methodology is preferred to other when is not possible to measure the excitation

- turbulence (civil and aerospace structures)
- waves (ships)
Motivations

- Developed **Output-Only techniques in NIMA code**
  - time (SSI – Juang [1994])
  - frequency (FDD – Brinker [2000], HTM – Agneni, Balis Crema, Coppotelli [2003])

- All methodologies do not allow the estimation of the generalized masses
  - unknown level of the input excitation

- This drawback can be solved considering the sensitivity of the modal parameters to structural variations (De Vries [1952], Coppotelli [2003])
  - several experimental tests with different mass “distributions”
  - generalized mass estimations from the variation of $f_n$
Motivations

- Validation of the enabled capabilities of the developed methodology from flight test data analysis
  - numerical model validation
  - vibration reduction control strategies
  - unsteady aerodynamic model identification
Results

• Numerical model

• Experimental model

• GROUND TESTS
  – Modal parameters

• FLIGHT TESTS
  – Aeroelastic stability analysis
  – Aeroelastic poles and modes estimates
  – Unsteady aerodynamic operator estimates
Results: initial correlation

- Wing span: 2.75 [m]  
- Chord: 0.402 [m]

**YAK-112 UAV**

- Length: 2.00 [m]
- Weight: 13.7 [Kg]
Summary of the FE model

<table>
<thead>
<tr>
<th>Element</th>
<th>Number</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>CQUAD4</td>
<td>3421</td>
<td>Fuselage, Wing, Tail</td>
</tr>
<tr>
<td>CTRIA3</td>
<td>92</td>
<td>Fuselage, Wing, Tail</td>
</tr>
<tr>
<td>CBAR</td>
<td>20</td>
<td>Struts</td>
</tr>
<tr>
<td>RBE2</td>
<td>20</td>
<td>Constrains</td>
</tr>
<tr>
<td>CONM2</td>
<td>1</td>
<td>Engine</td>
</tr>
</tbody>
</table>
Results: initial correlation

Numerical Modal

<table>
<thead>
<tr>
<th>Mode #</th>
<th>$f_n$ [Hz]</th>
<th>Mode Type</th>
<th>O-O Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>12.73</td>
<td>I Fuselage Torsion</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>13.60</td>
<td>I Wing Flapwise and I Tail Bending</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>25.37</td>
<td>I Fuselage Horizontal Bending &amp; I Fin Bending</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>37.98</td>
<td>I Wing Skew Torsion &amp; I Tail Bending</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>38.53</td>
<td>I Fuselage Horizontal Bending</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>46.52</td>
<td>II Wing Sym. Torsion</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mode #</th>
<th>$f_n$ [Hz]</th>
<th>$\zeta_n$ [%]</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>12.35</td>
<td>0.86</td>
</tr>
<tr>
<td>2</td>
<td>17.17</td>
<td>0.62</td>
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<tr>
<td>3</td>
<td>24.89</td>
<td>0.47</td>
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<tr>
<td>4</td>
<td>39.28</td>
<td>0.29</td>
</tr>
<tr>
<td>5</td>
<td>41.06</td>
<td>0.27</td>
</tr>
<tr>
<td>6</td>
<td>46.30</td>
<td>0.23</td>
</tr>
</tbody>
</table>
Objective:
Obtain an accurate dynamic FEM up to 50 Hz

Phase 1

FEM Improvement:
- Rear spar modeling;
- Re-definition of the wing skin material (orthotropic material)

Good correlation between the Experimental and Numerical mode shapes

Phase 2

Structural Updating:
Updating of the material properties through optimization process

Reduction of the eigenfrequency shifts between the numerical and experimental estimates
Design Variables

Spars \rightarrow E \rightarrow E_{11}, E_{22}, \nu_{12}, G_{12}

Wing Skin

Constraints

\[0.995 < \frac{f_n}{f_{n_{sp}}} < 1.005\]

\[0.995 < \frac{f_{n_{8}}}{f_{OMA}} < 1.005\]

\[0.995 < \frac{f_{n_{17}}}{f_{OMA}} < 1.005\]

Objective Function

\[G = \sqrt{(f_{8} - 17.17)^2 + (f_{17} - 46.30)^2}\]
## Results: FEM Updating

<table>
<thead>
<tr>
<th>Mode #</th>
<th>$f_n$ Num</th>
<th>$f_n$ OMA</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>12.78</td>
<td>12.35</td>
<td>3.4</td>
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<td>9</td>
<td>17.13</td>
<td>17.17</td>
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<tr>
<td>10</td>
<td>25.42</td>
<td>24.89</td>
<td>2.1</td>
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<tr>
<td>13</td>
<td>38.75</td>
<td>41.06</td>
<td>5.6</td>
</tr>
<tr>
<td>14</td>
<td>40.55</td>
<td>39.28</td>
<td>3.1</td>
</tr>
<tr>
<td>17</td>
<td>45.97</td>
<td>46.30</td>
<td>0.7</td>
</tr>
</tbody>
</table>

- Reduced eigenfrequency shift
- Well correlated mode shapes
Results: FEM Updating

**Fuselage torsion**

**First sym bending of the wings**

1st structural mode

2nd structural mode
Results: FEM Updating

Fuselage horizontal bending

Wing skew torsion

3rd structural mode

4th structural mode
Results: FEM Updating

Fuselage bending

Wing sym torsion

HTM Mode #5 $f_r = 41.06$ Hz $\zeta = 0.270\%$

5th structural mode

HTM Mode #6 $f_r = 46.30$ Hz $\zeta = 0.233\%$

6th structural mode
Results: Flight Tests

8 DOFs - $f_s = 256$ Hz

LMS SCADAS Mobile

Circuito di volo dello Yak

Pista di decollo
### Sensitivity of the modal parameters to velocity changes

#### Natural Frequency

<table>
<thead>
<tr>
<th>Mode #</th>
<th>( U_\infty ) [m/s]</th>
<th>( f_n ) [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>12.70</td>
<td>12.73</td>
</tr>
<tr>
<td>II</td>
<td>18.23</td>
<td>17.79</td>
</tr>
<tr>
<td>III</td>
<td>24.74</td>
<td>25.76</td>
</tr>
<tr>
<td>IV</td>
<td>43.24</td>
<td>38.25</td>
</tr>
<tr>
<td>V</td>
<td>48.20</td>
<td>43.74</td>
</tr>
</tbody>
</table>

#### Damping ratio

<table>
<thead>
<tr>
<th>Mode #</th>
<th>( U_\infty ) [m/s]</th>
<th>( \zeta_n ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1.69</td>
<td>1.69</td>
</tr>
<tr>
<td>II</td>
<td>1.17</td>
<td>1.21</td>
</tr>
<tr>
<td>III</td>
<td>0.86</td>
<td>0.83</td>
</tr>
<tr>
<td>IV</td>
<td>0.49</td>
<td>0.56</td>
</tr>
<tr>
<td>V</td>
<td>0.44</td>
<td>0.49</td>
</tr>
</tbody>
</table>
Results: Flight Tests

Aeroelastic poles and modes
Results: Flight Tests

Damping ratio vs flight velocity

- Damping ratios increase as velocity increases (experimentally)

STABLE AEROELASTIC SYSTEM
Results: Flight Tests

Synthesis of the Aeroelastic FRF

- Good correlation between the numerical and experimental estimates
- Numerical lower resonant peaks due to non-accurate modal masses estimate
- Effects of non-uniform flight condition
• Numerical Validation of the proposed procedure using numerical data simulating the flight tests
• NB: the piecewise-valued hypothesis for GAF is strictly valid for the (reduced) frequency equal to the imaginary part of the aeroelastic poles
• Perfect agreement between the GAF estimates and DLM direct evaluation
Results: Flight Tests

- Acceptable GAF identification in average for all the considered flight speeds
  - DLM poor representation of the flow field (attached and unviscous flow, thin aerodynamic surface)
  - Numerical damping needs revision
  - Generalized masses from experimental estimate
- Off-diagonal terms with very low signal-to-noise ratio
Concluding Remarks

- Improvement of a sensitivity-based updated procedure to deal with very large size FEM
  - Evaluation of the most important rows/columns to the rank of the sensitivity matrix through SVD
  - The most important updating parameters are retained in the updating procedure
  - Reduction of the required computer memory and time for calculation
  - “Physical” updated FEM

- Procedure successfully tested on structural components

- Encouraging results from VEGA – UCMEC FEM updating
  - Identification of structural part poorly discretized
  - Evident reduction of the eigenfrequency shifts
  - Increase of the correlation between transfer functions
An Output-Only-based procedure for the aeroelastic system identification has been developed.

- Aeroelastic poles (natural frequencies and damping ratio) and modal shapes were estimated.
- Generalized aerodynamic force:
  - Revision of the structural damping
  - Constant flight regimes
  - Modal masses from experimental estimate
- Aeroelastic numerical model updated with experimental data (both in-ground and in-flight).

Aeroelastic modal parameters of the UAV identified in its actual operative condition.