The application of Eulerian laser Doppler vibrometry to the on-line condition monitoring of axial-flow turbomachinery blades

by
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Scope

• Problem statement

• Eulerian laser Doppler vibrometry
  – Analytical and numerical study
  – Experimental verification

• Single-blade axial-flow rotor tests
  – Signal processing
    • Phase angle trends
    • Non-harmonic Fourier analysis
**Scope**

- Multi-blade rotor tests
  - Data processing
  - Artificial neural network implementation

- Conclusions

- Further work
Problem statement

• Turbomachines are critical to most industrial processes

• Power generation
  – Steam turbines
  – Forced and induced draft fans
  – Air Cooled Condenser (ACC) fans

• Blade health is of the utmost importance

• Frequent off-line inspection of blades not possible

• Online condition monitoring
On-line blade vibration measurement approaches

- Contact techniques
  - Strain gauge measurements
    - Good quality data (high SNRs)
    - High frequency resolution
    - Limited sensor lifespan

- Non-contact techniques
  - Blade tip Time-Of-Arrival
    - Infer blade vibration behaviour from pulses
    - Requires large amount of sensors for useful bandwidth
On-line blade vibration measurement approaches

• Non-contact techniques (*continued*)
  – Laser Doppler vibrometry
    • Large stand-off distance (up to 100m)
    • Large measurement bandwidth (0 to 24 MHz)
    • Large dynamic range (50 nm/s to 30 m/s)

• Direct blade vibration measurement
• Circumferential or axial
• Fixed (Eulerian) or moving (Lagrangian) reference frame
Laser Doppler Vibrometry: Measurement principle
Measurement approaches

- Lagrangian
  - Moving reference frame
  - Tracking laser vibrometry
  - Scanning laser vibrometer
  - Mirrors controlled to follow specific point on blade
  - Not industrially feasible

- Eulerian
  - Fixed reference frame
  - Laser beam is focused at fixed spatial point
  - Blades sweep through laser beam
  - Very short signals (max. 1/BPF)
  - Speckle noise
Eulerian Laser Doppler Vibrometry (ELDV): Analytical study

- Stationary LDV
- Moving cantilever beam
- Euler-Bernoulli formulation:
  - Lagrangian
    \[ v_L(x_L,t) = \frac{\partial w_L(x_L,t)}{\partial t} = \sum_{j=1}^{\infty} W_j(x_L) \cdot \frac{dq_j(t)}{dt} \]
  - Eulerian
    \[ x_E = ct \]
    \[ v_E(c,t) = \sum_{j=1}^{\infty} W_j(ct) \frac{d}{dt} q_j(t) \quad \text{for} \quad 0 \leq t \leq \frac{l}{c} \]

Amplitude modulation
ODS via demodulation
ELDV numerical simulation

- Select $c$ and $f_s$

- Consider Lagrangian vibration responses at $N = \left\lfloor \frac{L}{(c \cdot \Delta t)} \right\rfloor$ equi-spaced measurement positions over the entire beam length:

$$x_L = \left\{ x_{L1}, x_{L2}, \ldots, x_{L(N-1)}, x_{LN} \right\}$$

at $N$ discrete time instants:

$$T = \left\{ t_1, t_2, \ldots, t_{N-1}, t_N \right\}$$

- Obtain ELDV for $c$ by incrementing the measurement position with each time step
ELDV numerical simulation

\[ L = 112.5 \text{ mm} \]
\[ c = 46.16 \text{ m/s} \]
\[ f_s = 20 \text{ kHz} \]

\[ \Rightarrow N = 48 \]
ELDV numerical simulation

$k = 1$

Lagrangian Vibration Response Matrix
ELDV numerical simulation

Lagrangian Vibration Response Matrix

$k = 1$

$k = 2$
ELDV numerical simulation

\[ k = 1 \]
\[ k = 2 \]
\[ k = 3 \]

Lagrangian Vibration Response Matrix
**ELDV numerical simulation**

- Non-integer $k$: Calculate new Lagrangian response matrix for each new value

- Computationally expensive

- Two dimensional interpolation
  - Spatial & time domain

- Higher values of $k$ reduces error

- Lagrangian matrix resolution
ELDV experimental study

- Draw wire unit
- Cantilever beam
- Chassis
- VibroPet electrodynamic shaker
- Forces transducer
- Rails
ELDV experimental study

- $c = 0.54 \text{ m/s}$
- Sinusoidal excitation
  - ODS extraction
  - Speckle noise
- White noise excitation
  - FRF peaks visible
  - ODS extraction
Single-blade test rotor

- Eliminate multi-blade phenomena
  - Global mode shapes
  - Mistuning
- Air-jet excitation
- Air-jet back pressure
- Shaft encoder
- Simulated damage
  - 1 mm wide slot
  - 0 mm to 16 mm
Single-blade rotor

- 720 RPM (12 Hz)
  - ELDV
    - 1.8 ms
    - $\Delta f = 540$ Hz
  - TLDV
    - 38.1 ms
    - $\Delta f = 26$ Hz

- Amplitude & phase angle changes
  - Systematic
  - Abrupt
## Non-Harmonic Fourier Analysis (NHFA)

<table>
<thead>
<tr>
<th>NHFA</th>
<th>HFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H(m, \omega) = a(\omega) \times C(m, \omega) + b(\omega) \times S(m, \omega)$</td>
<td>$y(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos n\omega_0 t + b_n \sin n\omega_0 t)$</td>
</tr>
</tbody>
</table>

- $\omega_0 = \frac{2\pi}{\tau}$

### Calculations

<table>
<thead>
<tr>
<th>$a(\omega)$</th>
<th>$a_n = \frac{2}{\tau} \int_{-\tau/2}^{\tau/2} y(t) \cos n\omega_0 t , dt$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b(\omega)$</td>
<td>$b_n = \frac{2}{\tau} \int_{-\tau/2}^{\tau/2} y(t) \sin n\omega_0 t , dt$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$y(t) = \cos(\omega t + \phi)$</th>
<th>$a(\omega) = \cos \phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b(\omega) = -\sin \phi$</td>
<td>$y(t) = \cos(k\omega_0 t + \phi)$</td>
</tr>
<tr>
<td>$a_k = \cos \phi$</td>
<td>$b_k = -\sin \phi$</td>
</tr>
</tbody>
</table>
\[ y(t) = \cos \left( \left( \omega_{\text{ref}} + \Delta \omega \right) t + \phi \right) \]

\[ a(\omega_{\text{ref}}) = \left( \frac{2 \omega_{\text{ref}}}{\omega_{\text{ref}} t + \sin \omega t} \right) \left[ \frac{\sin \left( \Delta \omega \tau / 2 \right)}{\Delta \omega} + \frac{\sin \left( 2 \omega_{\text{ref}} + \Delta \omega \right) \tau / 2}{2 \omega_{\text{ref}} + \Delta \omega} \right] \cos \left[ \phi + \left( \omega_{\text{ref}} + \Delta \omega \right) \tau / 2 \right] \]

\[ b(\omega_{\text{ref}}) = -\left( \frac{2 \omega_{\text{ref}}}{\omega_{\text{ref}} t - \sin \omega t} \right) \left[ \frac{\sin \left( \Delta \omega \tau / 2 \right)}{\Delta \omega} - \frac{\sin \left( 2 \omega_{\text{ref}} + \Delta \omega \right) \tau / 2}{2 \omega_{\text{ref}} + \Delta \omega} \right] \sin \left[ \phi + \left( \omega_{\text{ref}} + \Delta \omega \right) \tau / 2 \right] \]

- Phase shift
- Frequency shift
- Can be exploited for condition monitoring
Finite Element Model (FEM)

- Validate experimental measurements
- FRF-based model updating
  - Node resolution
- ELDV simulation
- Damage simulation
  - Element deletion
  - Validation
Unwrapped Phase Angle (UPA) trends

[Graph showing phase angle shift against damage level]
UPA trend sensitivity analysis

Experimental:
Maximum Absolute UPA Trend (MAUPAT)
**Multi-blade rotor**

- 5-blade rotor

- Multi-blade phenomena  
  - Global mode shapes  
    - Erroneous damage detection  
    - Damage “masking”  
  - Blade mistuning  
    - Blade clamping  
      - Epoxy  
      - Clamp bolt torque  
  - Blade spacing  
    - Harmonics
Multi-blade rotor

- Test at various rotor speeds
  - 720, 960, 1200, 1440 RPM

- Multiple blade damage scenarios

- Two ELDV measurement positions
  - Forced
  - Free
FEM

- Solid elements
- Scan node reduction
- FRF-based model updating
- Excitation
TLDV comparison

Measured @ 1200 RPM

Simulated @ 1200 RPM

Measured @ 1440 RPM

Simulated @ 1440 RPM
Phase and amplitude irregularities

- FEM TLDV
- RMS values
- Blade 1\textsuperscript{st} bending mode natural frequency
- Natural frequency coincides with rotor speed order
- RMS useful as a damage indicator
MAUPAT around $f_1$
$\sigma_{\text{MAUPAT}}$ around $f_1$
Average $\sigma_{\text{MAUPAT}}$
Average $\sigma_{MAUPAT}$: Multiple blade damage
Artificial Neural Network implementation

![Diagram showing various graphs for different RPMs and damage cases](image)

- **Damage level, $D_b$**
- **720 RPM**
- **960 RPM**
- **1200 RPM**
- **1440 RPM**

Legend:
- Blade #1
- Blade #2
- Blade #3
- Blade #4
- Blade #5
ELDV natural frequency information

- Run-down and run-up signatures
- Blade natural frequency coincides with rotor order
- RMS peaks
## ELDV natural frequency estimation

<table>
<thead>
<tr>
<th>Blade #</th>
<th>FRF frequency [Hz]</th>
<th>Estimated frequency [Hz]</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>106.25</td>
<td>109.48</td>
<td>3.04</td>
</tr>
<tr>
<td>2</td>
<td>137.5</td>
<td>138.11</td>
<td>0.44</td>
</tr>
<tr>
<td>3</td>
<td>103.125</td>
<td>105.04</td>
<td>1.89</td>
</tr>
<tr>
<td>4</td>
<td>137.5</td>
<td>138.34</td>
<td>0.61</td>
</tr>
<tr>
<td>5</td>
<td>109.375</td>
<td>111.64</td>
<td>2.07</td>
</tr>
</tbody>
</table>
Conclusions

• ELDV is a feasible on-line rotor blade condition monitoring tool

• NHFA provides health deterioration indicators
  – MAUPAT
  – RMS, Correlation coefficient
  – Neural network implementation

• Multiple ELDV measurement positions are advantageous

• Blade natural frequencies can be estimated from rotor run-down and run-up events
Further work

- Industrial testing
  - Operating variables
  - Reflectivity
    - Increased laser beam power
      - Safety
    - Phased-based microwave sensors
      - Beam dispersion (spatial averaging)

- Effect of actual cracks
  - Nonlinear stiffness

- Rotors with high blade numbers
Acknowledgements

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Questions

Thank you!