Continuous-Scan Laser Vibrometry with Unmeasured Input Forces and Application to a 20kW Wind Turbine

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1. Motivation:

- Wind Turbines must be carefully designed to avoid failure due to vibration.
- Tests used to verify that the turbine meets design requirements and to characterize wear or damage, but are difficult to perform.
  - Difficult to attach sensors to the structure.
- Laser vibrometer alternative:
  - Non-contact laser simplifies setup
  - Measurements can be performed from the ground.
  - However, mode shapes difficult to obtain since test time at each measurement point is long and measurement at several points simultaneously is prohibitively expensive.

2. Background:

- Continuous-Scan Laser Vibrometry (CSLDV):
  - Velocity is measured as the laser spot sweeps continuously over the structure (as opposed to measuring each point sequentially).
  - Accelerates measurements by effectively measuring the response at many points simultaneously.
- However, existing methods for treating CSLDV measurements require controlled input forces – need a method that can utilize the unmeasured forces exerted by the wind.

3. Methods:

- Assume Linear Time Invariant Structure (LTI)

$$\dot{x} = \mathbf{A}x + \mathbf{B}u \qquad y = \mathbf{C}x + \mathbf{D}u \qquad M\ddot{q} + C\dot{q} + Kq = F(t)$$

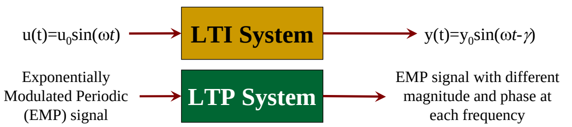
  - CSLDV: measurement point continuously scans over the structure

$$\dot{x} = \mathbf{A}x + \mathbf{B}u \qquad y = \mathbf{C}(t)x$$

  - Limit to closed (periodic) scanning pattern

$$\mathbf{C}(t) = C(T_A + t)$$

- CSLDV measurements can be treated as the output of a Linear Time Periodic (LTP) system.
- Allen et al. recently created a new frequency domain algorithm for LTP system Identification based on the Harmonic Transfer Function concept by Wereley & Hall:



- As for LTI systems, the HTF can be expressed in terms of the modes:

$$\mathbf{G}(\omega) = \sum_{r=1}^{N}\sum_{l=-\infty}^{\infty} \frac{\bar{\mathbf{C}}_{r,l}\bar{\mathbf{B}}_{r,l}}{i\omega - (\lambda_r - il\omega_A)} + \mathbf{D} \qquad C(t)\psi_r(t) = \sum_{n=-\infty}^{\infty} C_{r,n} e^{jn\omega_A t}$$

$$\bar{\mathbf{C}}_{r,l} = \begin{bmatrix} \cdots & C_{r,-1-l}^{\ T} & C_{r,-l}^{\ T} & C_{r,1-l}^{\ T} & \cdots \end{bmatrix}^T \qquad L_r(t)^T B(t) = \sum_{n=-\infty}^{\infty} B_{r,n} e^{jn\omega_A t}$$

$$\bar{\mathbf{B}}_{r,l} = \begin{bmatrix} \cdots & B_{r,l+1} & B_{r,l} & B_{r,l-1} & \cdots \end{bmatrix}$$

- Output Only Identification

$$\left[S_{yy}(\omega)\right] = \mathbf{G}(\omega) S_{uu}(\omega) \mathbf{G}(\omega)^H = \sum_{r=1}^{N}\sum_{l=-\infty}^{\infty} \frac{\bar{\mathbf{C}}_{r,l}\mathbf{W}(\omega)_{r,l}\bar{\mathbf{C}}_{r,l}^{\ H}}{\left[i\omega - (\lambda_r - il\omega_A)\right]\left[i\omega - (\lambda_r - il\omega_A)\right]^H}$$

White

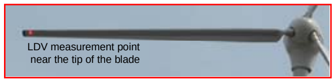
- Differences:
  - Each mode appears at many frequencies, spaced by integer multiples of fundamental frequency ω_A.
  - Mode Shapes $\bar{\mathbf{C}}_{r,l}$ comprised of <u>coefficients of a Fourier series expansion</u> of the time-varying shapes.

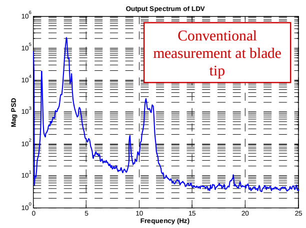
4. Experimental Validation:

- Field test on 20kW wind turbine manufactured by Renewegy LLC in Oshkosh, WI.
  - 10m diameter rotor, 30m tower height.
  - Rotor was parked with the brake applied during the test.
  - The blade vibrated due to the unmeasured forces exerted by the wind
  - 3.5 m/s max wind speed (light wind) during the tests.

5. Results:

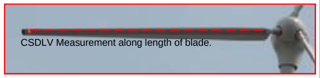
- Conventional OMA Measurement
  - Laser positioned at a fixed point at the tip of the blade.
  - 10 minutes required to obtain the spectrum.
  - Several modes below 15Hz are significantly excited.
  - Mode shapes are not obtained.

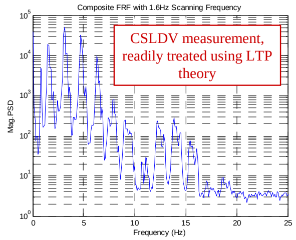


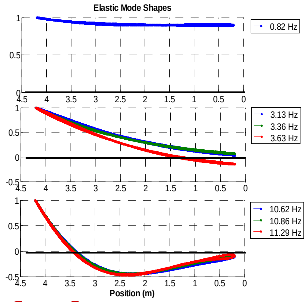


Mode	Fixed point OMA on tower	CSLDV OMA on tower
1st Tower	0.81Hz	0.78Hz
Flap Wise Bending 1	3.13Hz 3.37Hz 3.63Hz	3.13Hz 3.36Hz 3.62Hz
Edge Wise Bending 1	4.38Hz	-
?	9.13Hz	-
Flap Wise Bending 2	10.63Hz 10.94Hz 11.25Hz	10.62Hz 10.86Hz 11.29Hz

- CSLDV Measurement
  - Laser scans a line along the length of the blade while measuring.
  - Spectrum and mode shapes at many points obtained from two measurements totaling 20 minutes.







6. Conclusions & Outlook:

- Output-only CSLDV is experimentally viable and can provide significant time savings for large structures.
  - Application to a real turbine blade acquired mode shapes in **minutes**
  - Conventional LDV would require additional equipment and **several hours** of measurements to obtain the mode shapes.
- Lessons learned are being used to extend LTP output only identification methods to characterize nonlinear systems about periodic limit cycles.

References

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- N. M. Wereley, "Analysis and Control of Linear Periodically Time Varying Systems," PhD Thesis, Department of Aeronautics and Astronautics, Cambridge: Massachusetts Institute of Technology, 1991.