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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

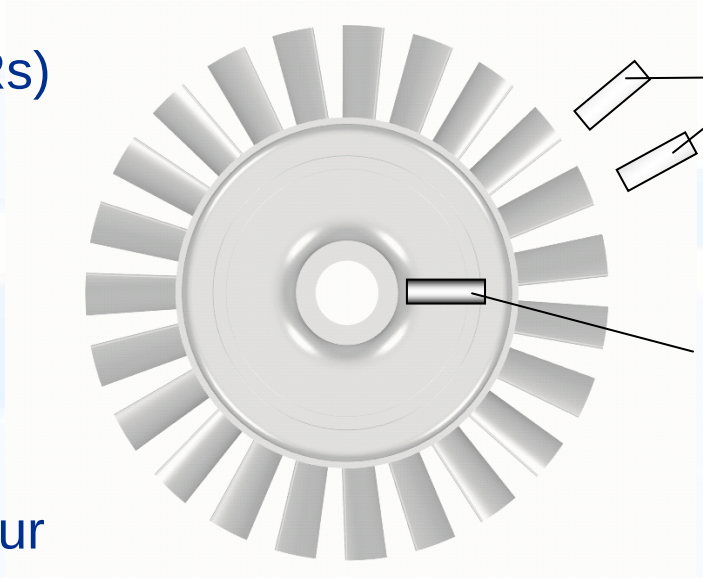
- Multi-blade rotor tests
  - Data processing
  - Artificial neural network implementation
- Conclusions
- Further work

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



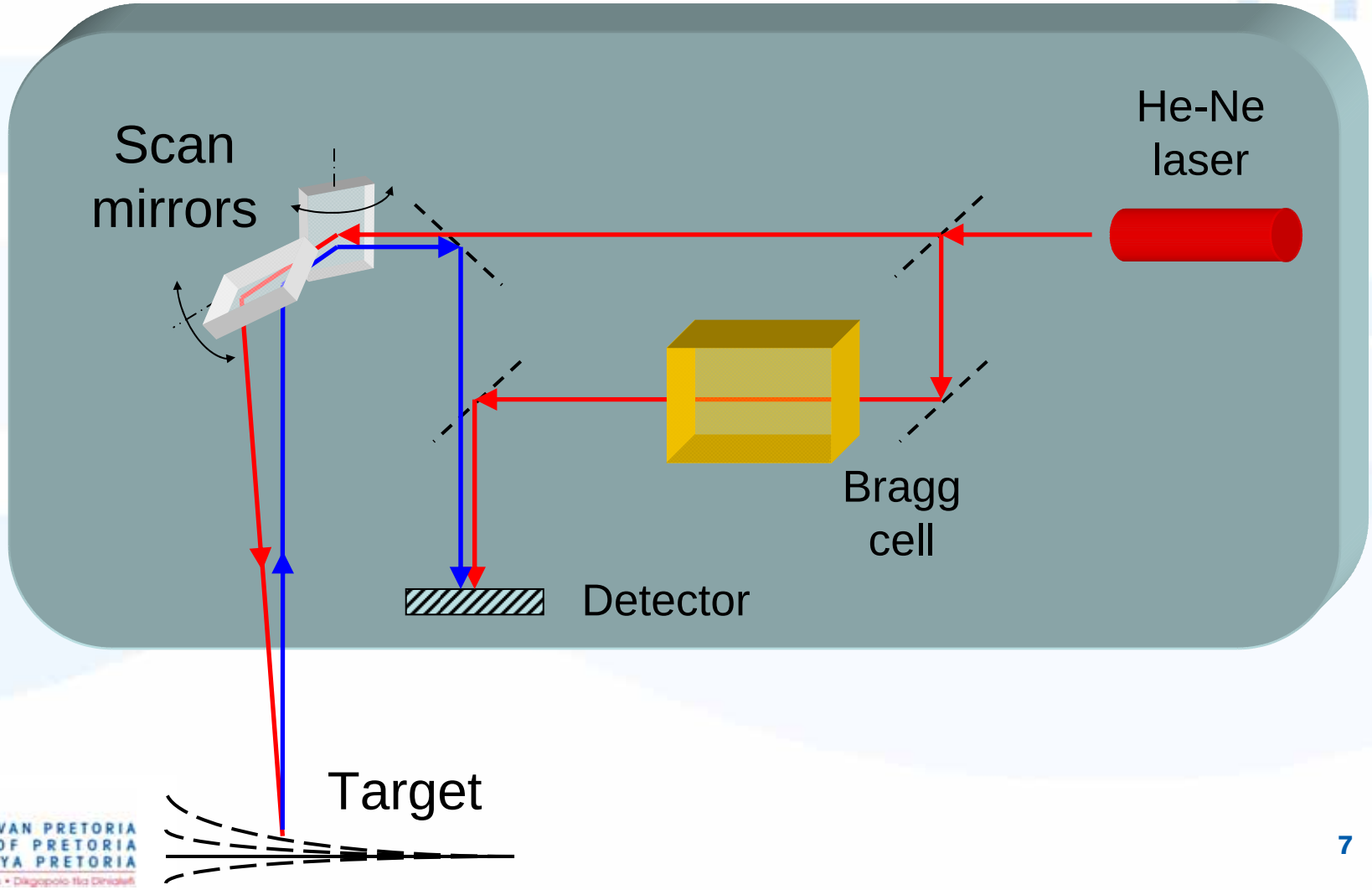
- Non-contact techniques
  - Blade tip Time-Of-Arrival
    - Infer blade vibration behaviour from pulses
    - Requires large amount of sensors for useful bandwidth

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

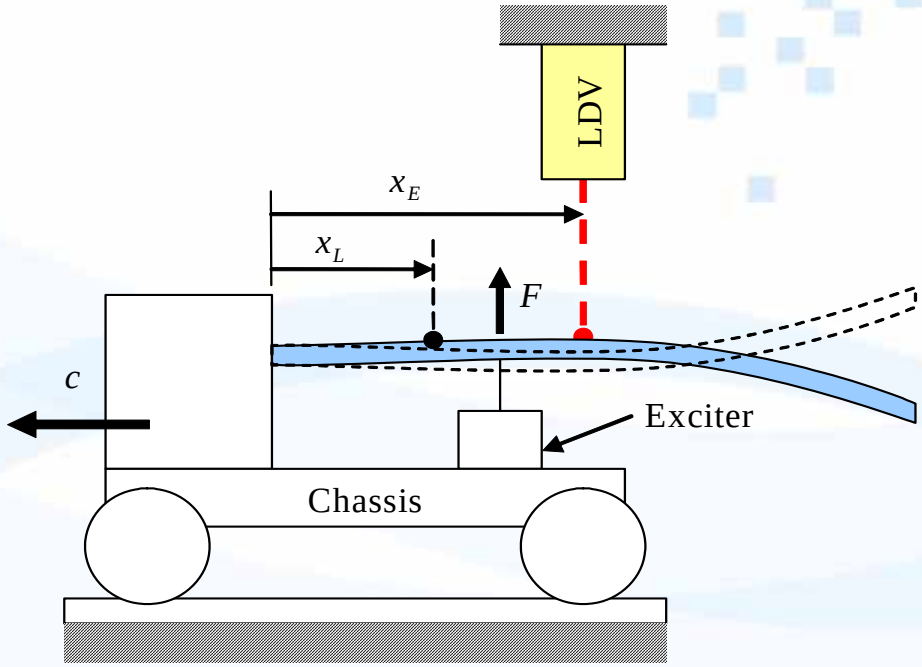
- Lagrangian
  - Moving reference frame
  - Tracking laser vibrometry
  - Scanning laser vibrometer
  - Mirrors controlled to follow specific point on blade
  - Not industrially feasible

- Eulerian
  - Fixed reference frame
  - Laser beam is focussed 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

$$x_E = ct$$

$$v_E(c,t)=\sum_{j=1}^{\infty}W_j(ct)\frac{d}{dt}q_j(t) \text{ for } 0\le t\le\frac{l}{c}$$

→ Amplitude modulation

→ ODS via demodulation

ELDV numerical simulation

- Select c and f_s
- Consider Lagrangian vibration responses at $N = \lfloor L/(c \cdot \Delta t) \rfloor$ equi-spaced measurement positions over the entire beam length:

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

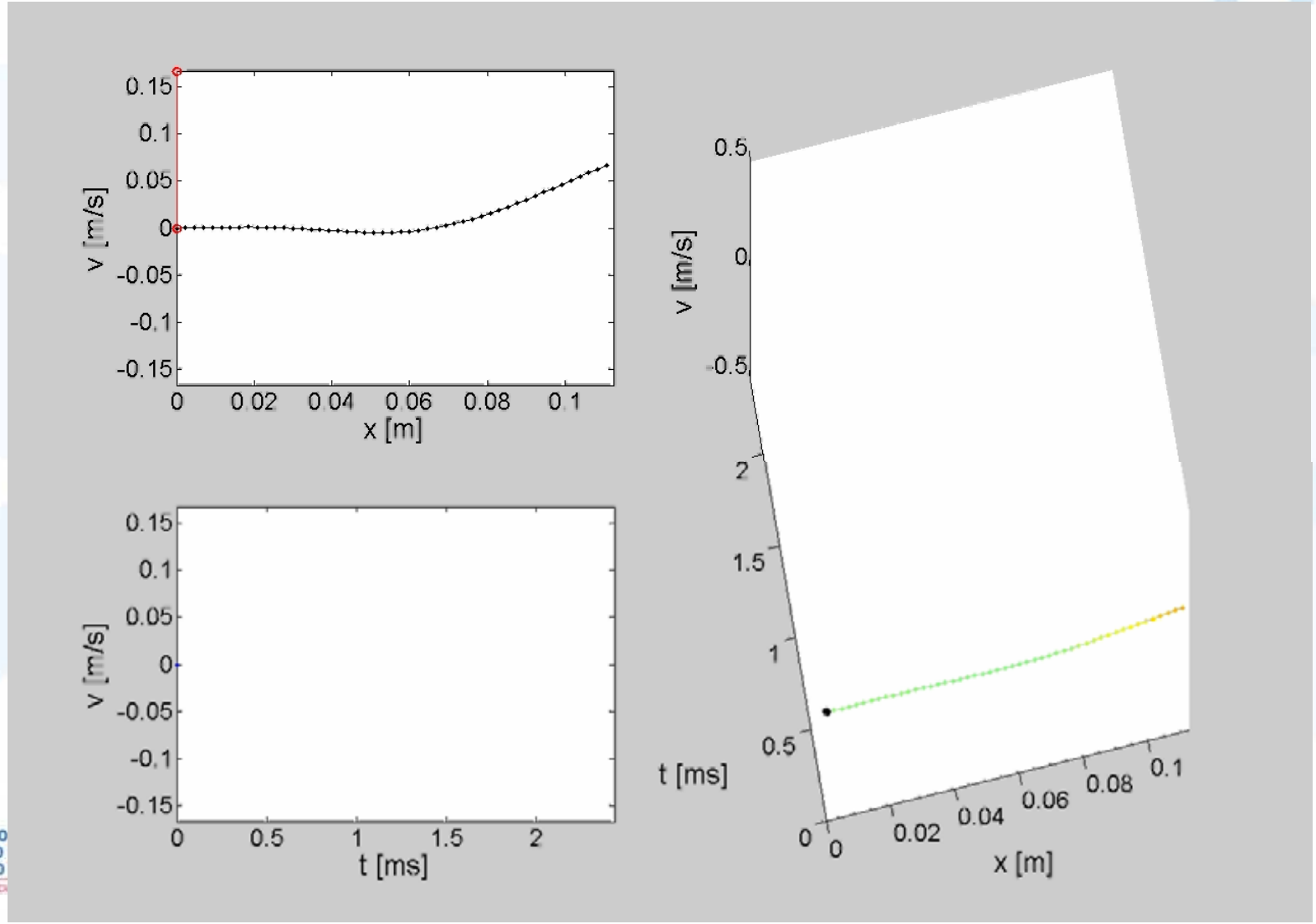
at N discrete time instants:

$$\boxed{T = \left\{ t_1, \quad t_{2,} \quad \ldots, \quad t_{N-1}, \quad t_N \right\}}$$

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

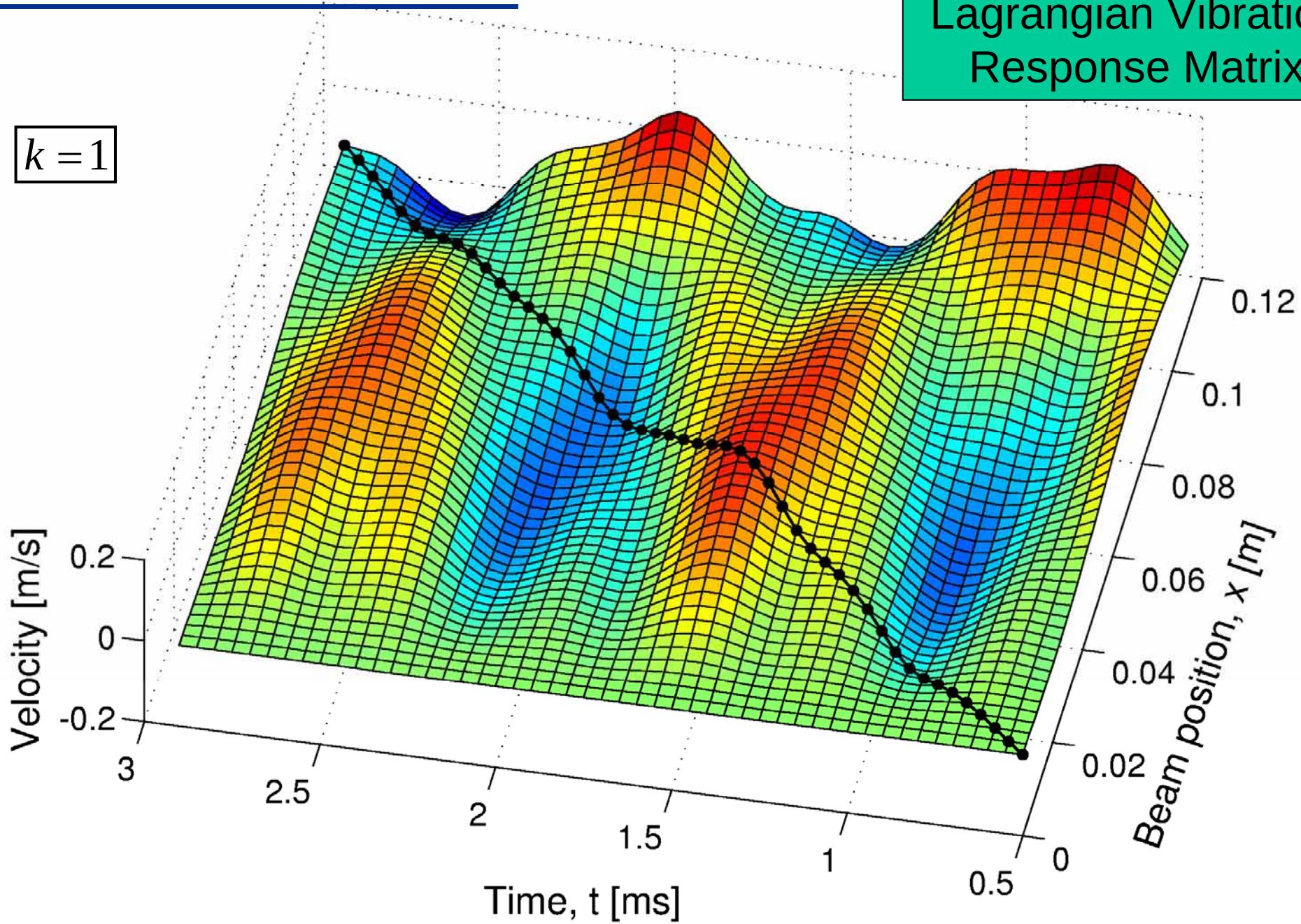
ELDV numerical simulation

$$L = 112.5\,\text{mm}$$
$$c = 46.16\ \text{m/s}$$
$$f_s = 20\,\text{kHz}$$
$$\Rightarrow N = 48$$



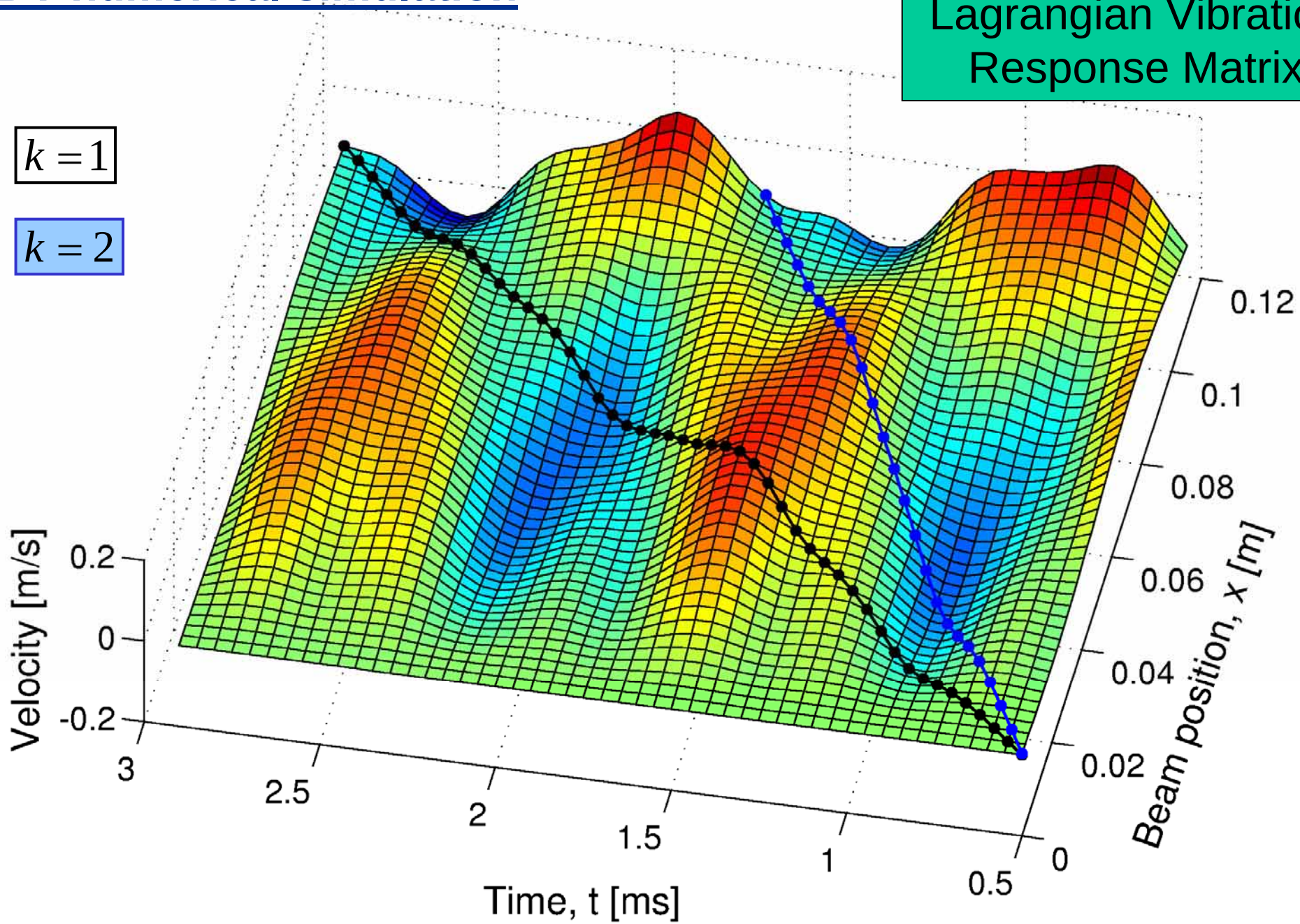
ELDV numerical simulation

Lagrangian Vibration Response Matrix



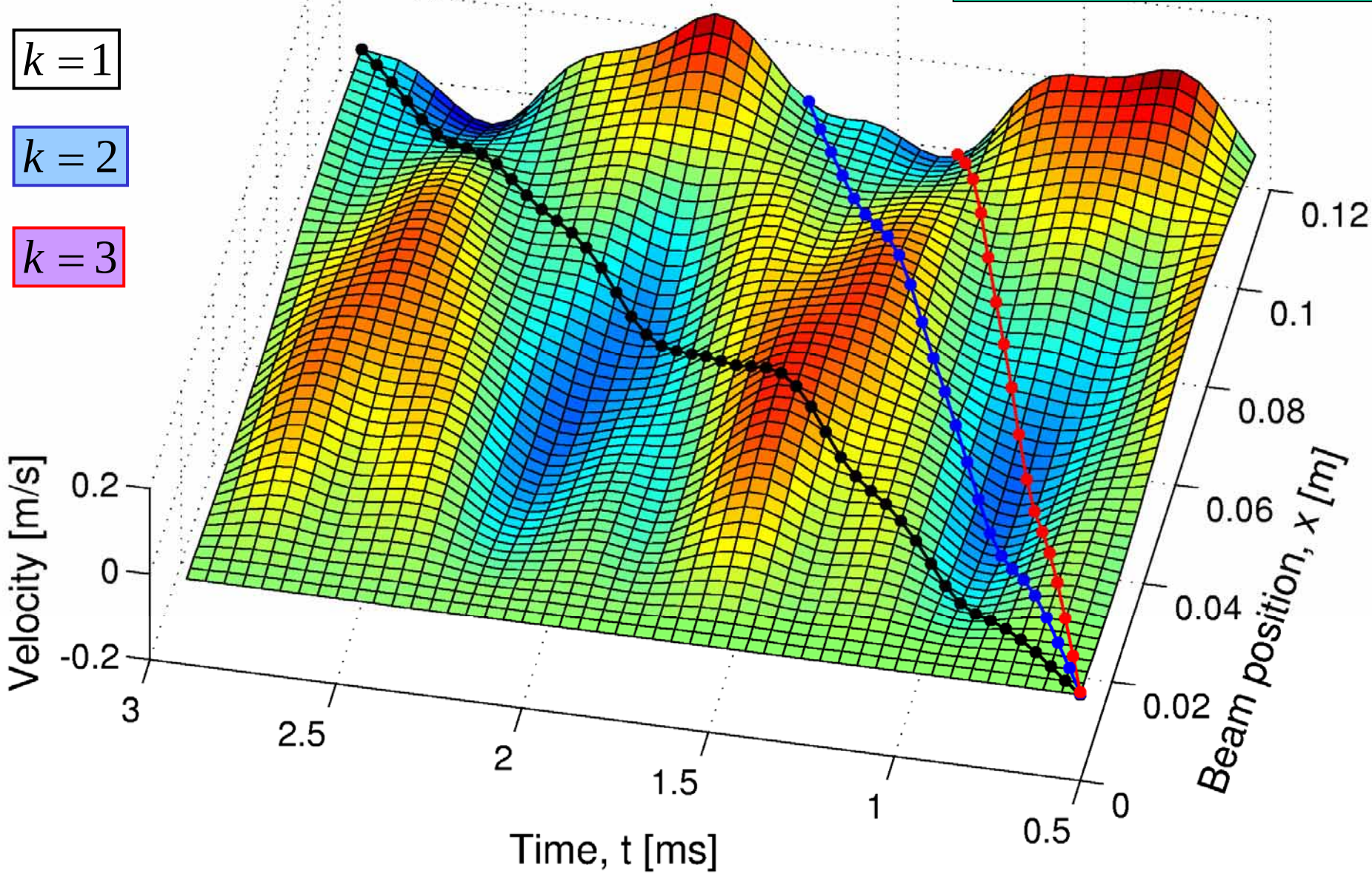
ELDV numerical simulation

Lagrangian Vibration Response Matrix



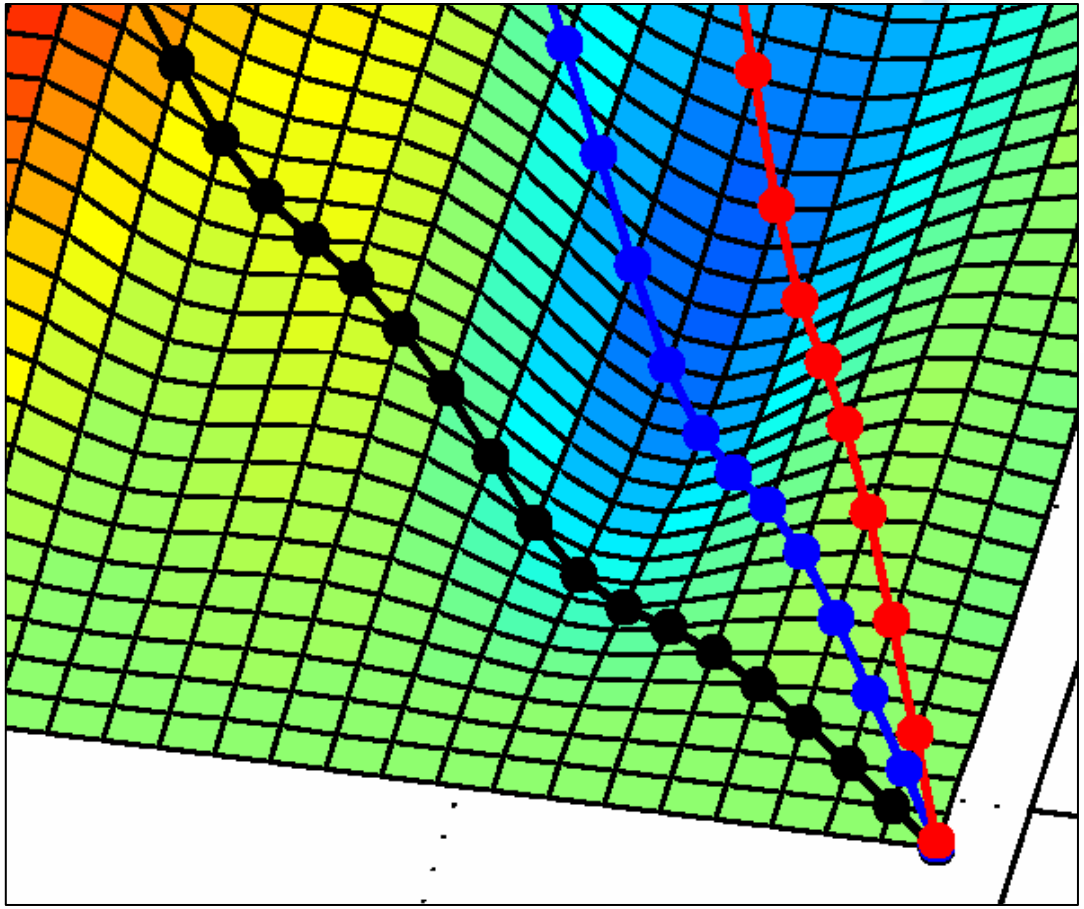
ELDV numerical simulation

Lagrangian Vibration Response Matrix

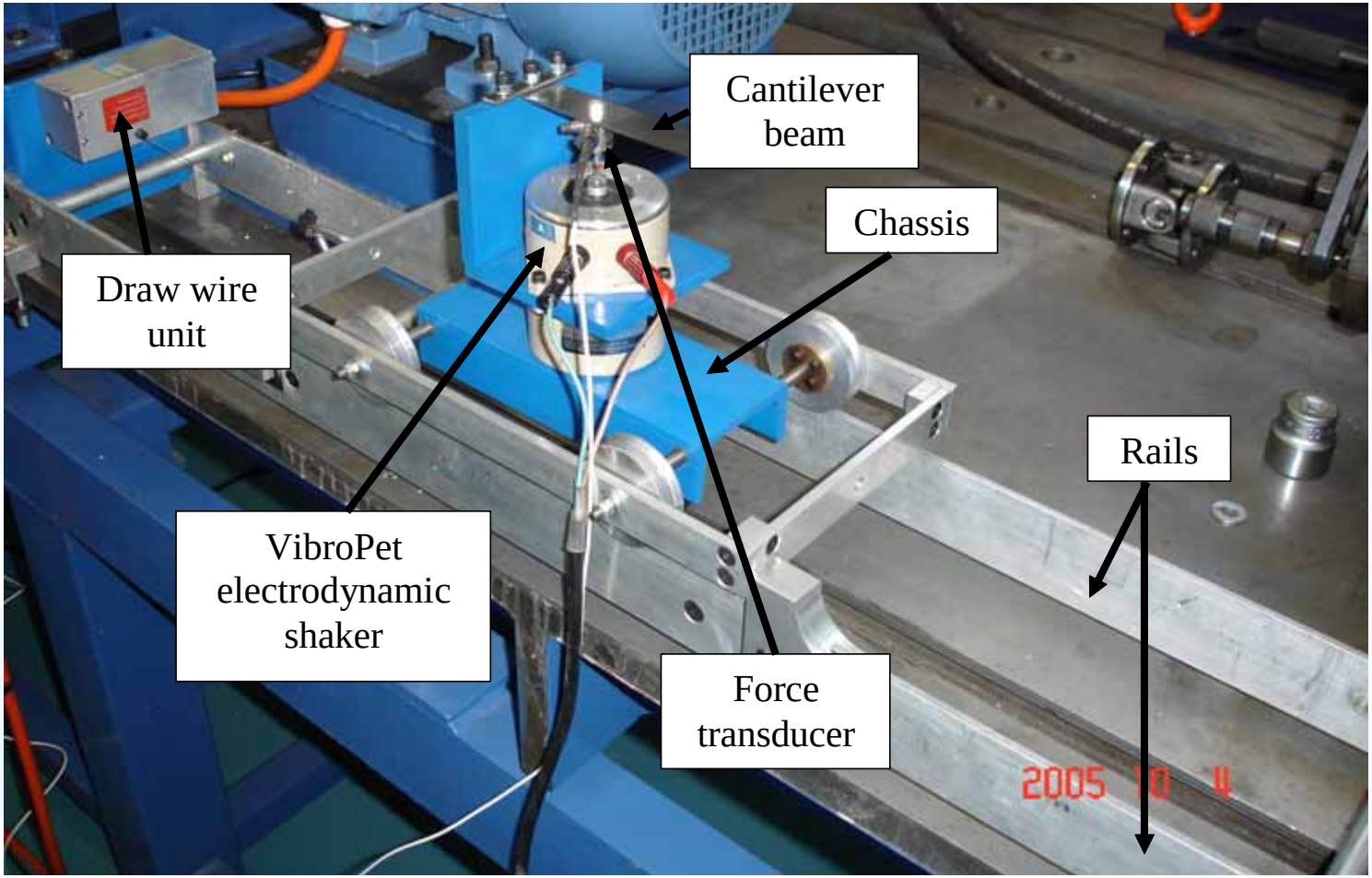


ELDV numerical simulation

- 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

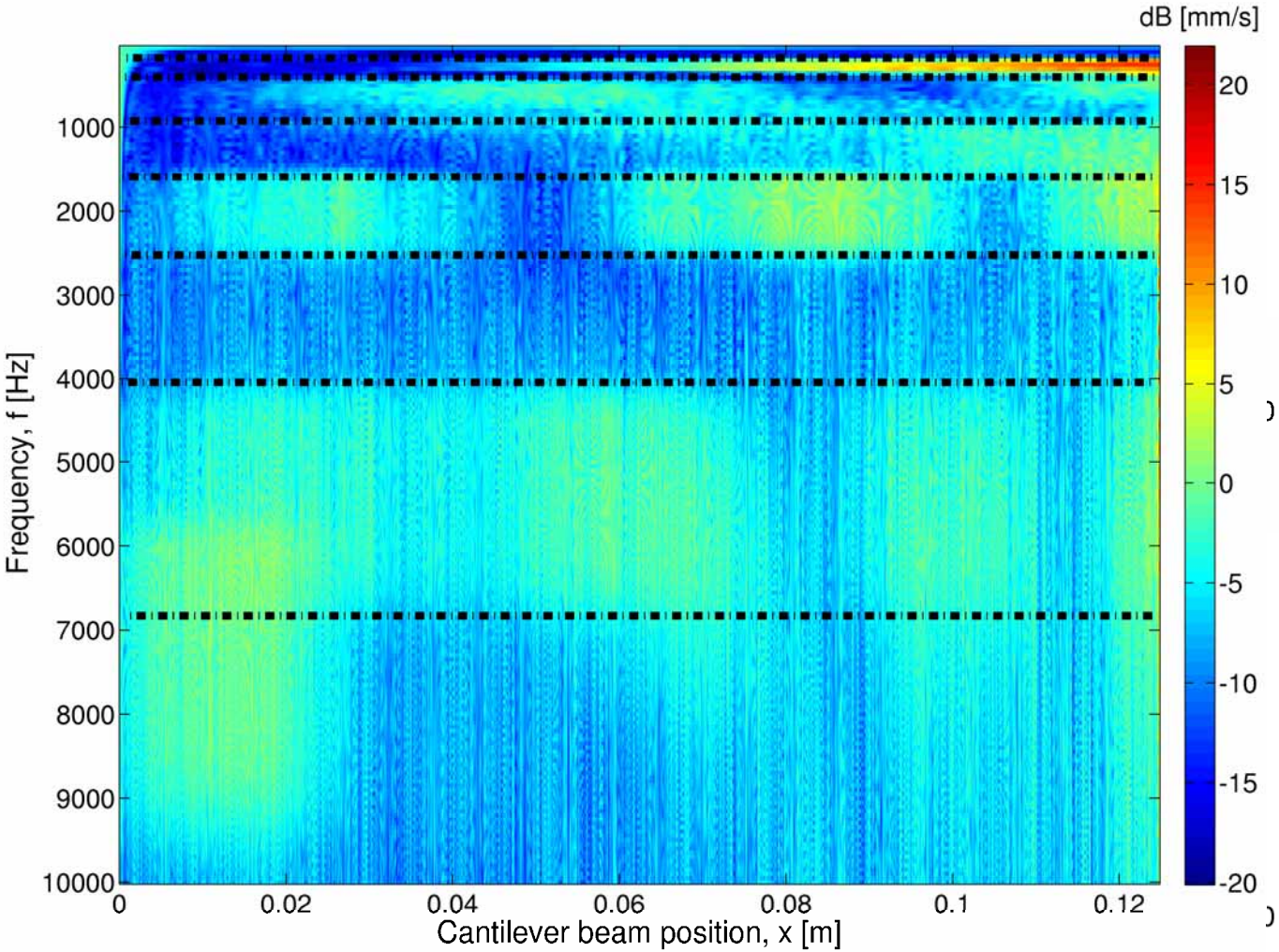


ELDV experimental study



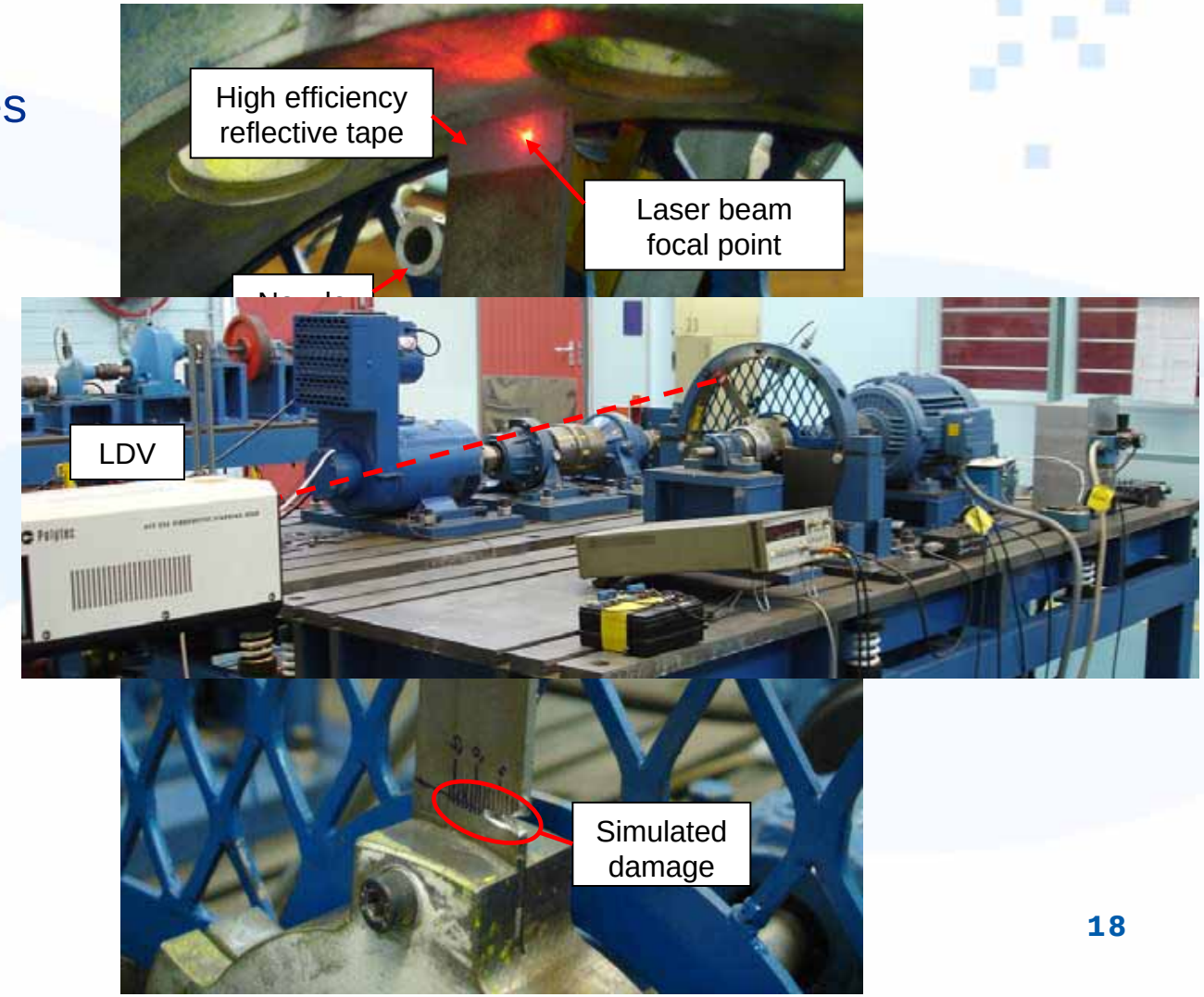
ELDV experimental study

- c = 0.54 m/s
- Sinusoidal excitation
  - ODS extraction
  - Speckle noise
- White noise excitation
  - FRF peaks visible
  - ODS extraction



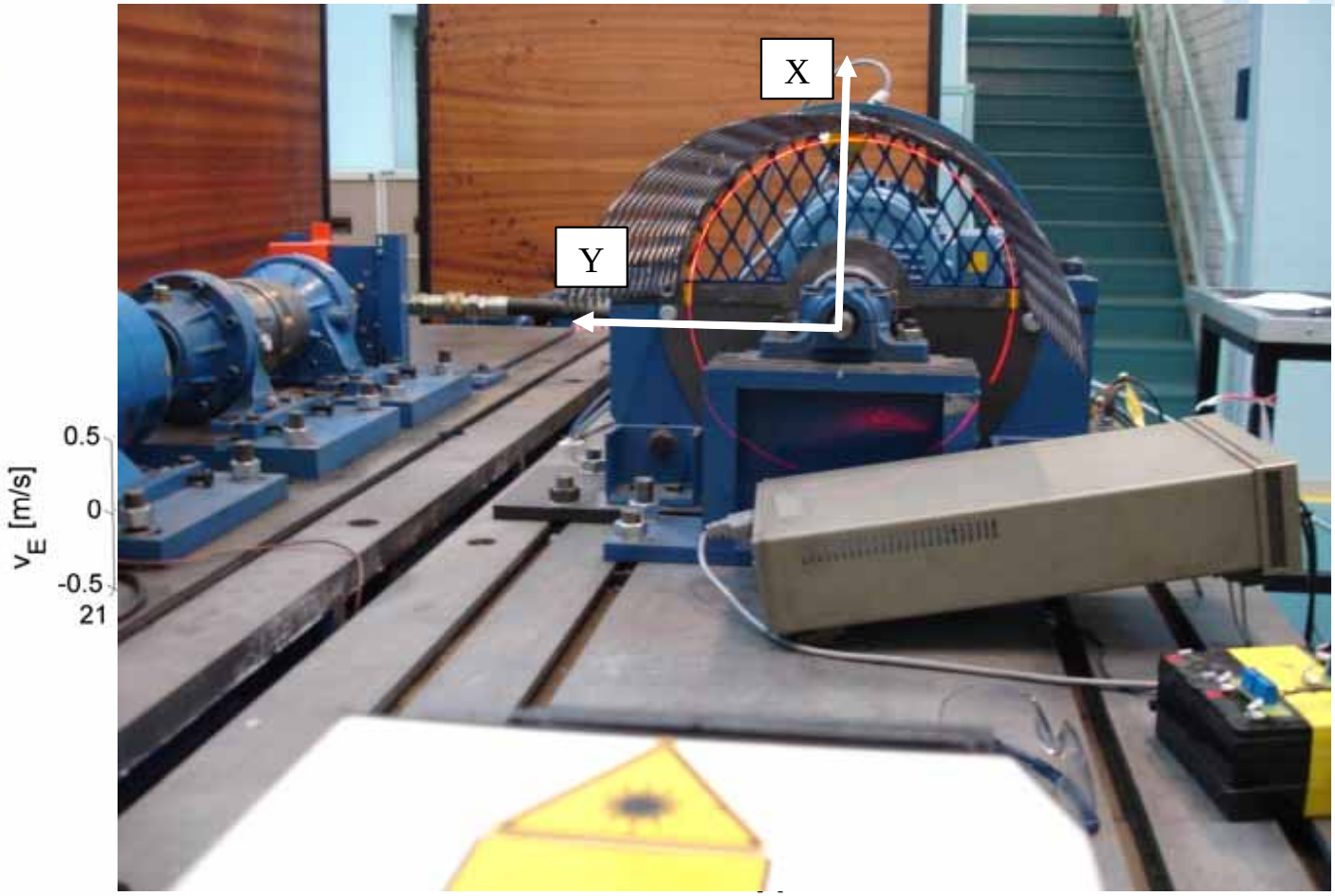
Single-blade test rotor

- 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
    - Δf = 540 Hz
  - TLDV
    - 38.1 ms
    - Δf = 26 Hz
- Amplitude & phase angle changes
  - Systematic
  - Abrupt



Non-Harmonic Fourier Analysis (NHFA)

NHFA	***HFA***
$H(m,\omega)=a(\omega)\times C(m,\omega)+b(\omega)\times S(m,\omega)$	$y(t)=\frac{a_0}{2}+\sum_{n=1}^{\infty}\left(a_n\cos n\omega_0 t+b_n\sin n\omega_0 t\right)$
	$\omega_0=2\pi/\tau$
$a(\omega)=\int_{-\tau/2}^{\tau/2}y(t)\cos(\omega t)dt \Big/ \int_{-\tau/2}^{\tau/2}\cos^2(\omega t)\,dt$	$a_n=\frac{2}{\tau}\int_{-\tau/2}^{\tau/2}y(t)\cos n\omega_0 t\,dt$
$b(\omega)=\int_{-\tau/2}^{\tau/2}y(t)\sin(\omega t)dt \Big/ \int_{-\tau/2}^{\tau/2}\sin^2(\omega t)\,dt$	$b_n=\frac{2}{\tau}\int_{-\tau/2}^{\tau/2}y(t)\sin n\omega_0 t\,dt$
$y(t)=\cos(\omega t+\phi)$	$y(t)=\cos(k\omega_0 t+\phi)$
$a(\omega)=\cos\phi$ $b(\omega)=-\sin\phi$	$a_k=\cos\phi$ $b_k=-\sin\phi$

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NHFA

$$y(t) = \cos\left[\left(\omega_{ref} + \Delta\omega\right)t + \phi\right]$$

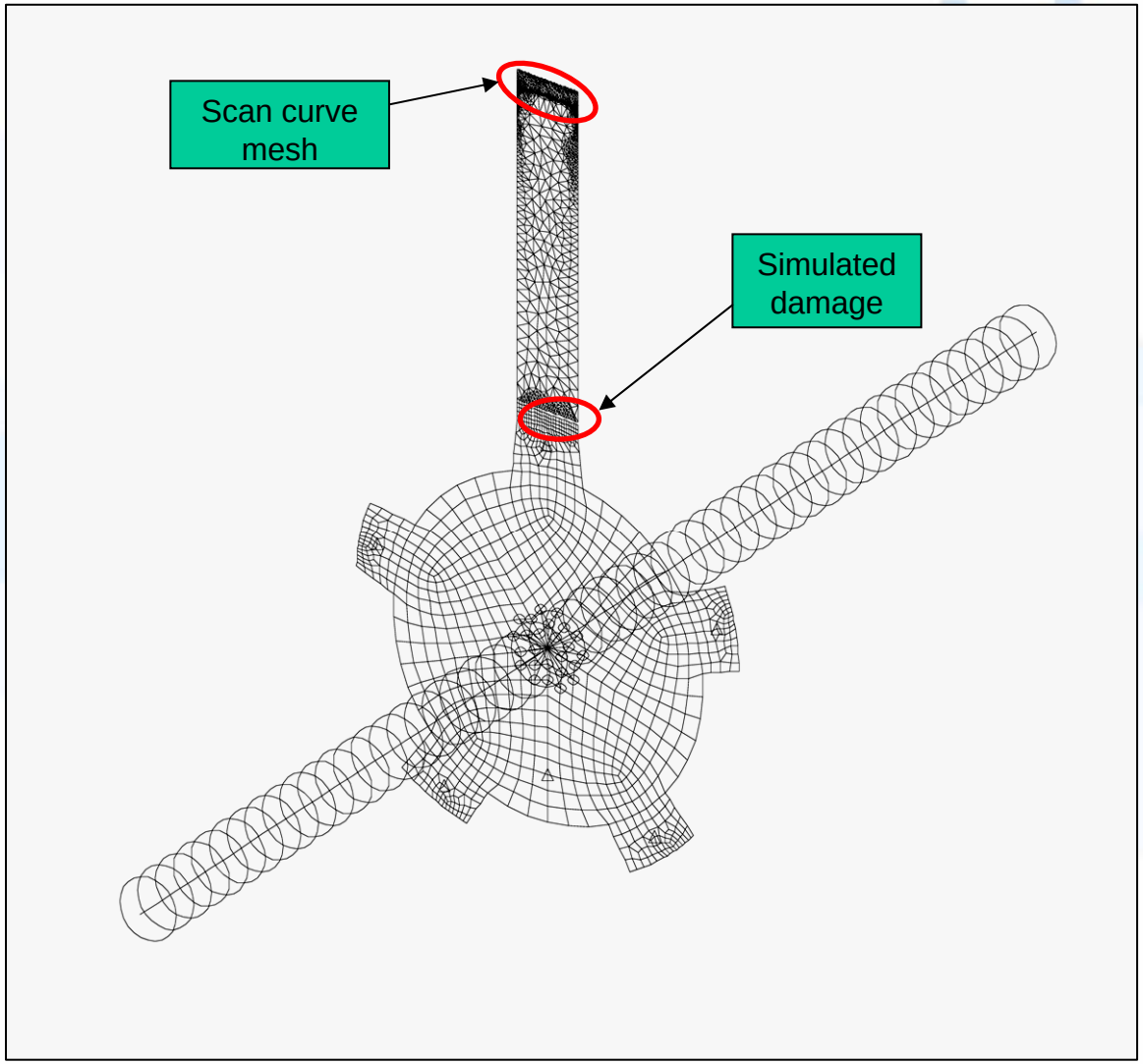
$$a\left(\omega_{ref}\right) = \left(\frac{2\omega_{ref}}{\omega_{ref}\tau + \sin\omega\tau}\right)\left[\frac{\sin\left(\Delta\omega\tau/2\right)}{\Delta\omega} + \frac{\sin\left(2\omega_{ref} + \Delta\omega\right)\tau/2}{2\omega_{ref} + \Delta\omega}\right]\cos\left[\phi + \left(\omega_{ref} + \Delta\omega\right)\tau/2\right]$$

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

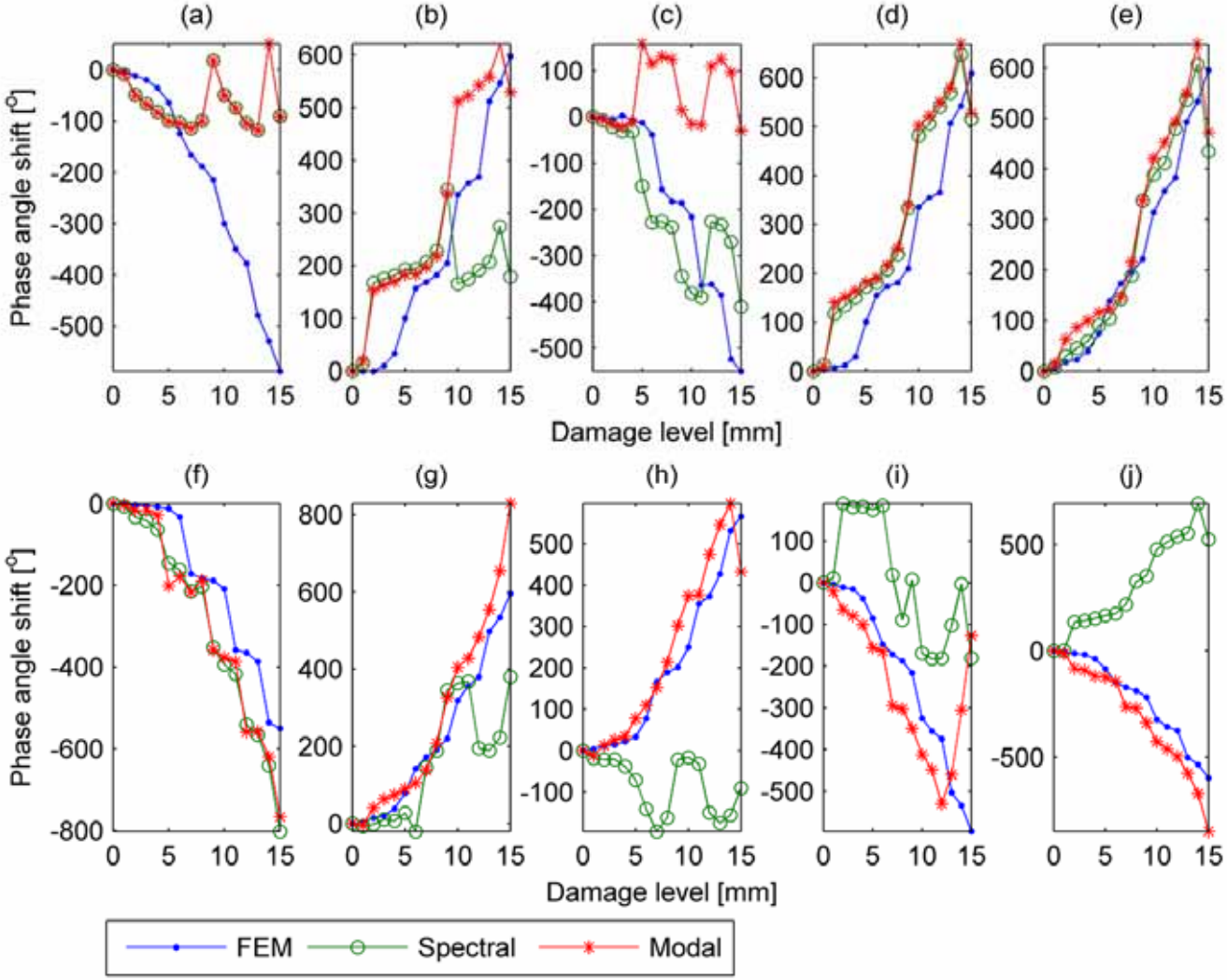
- Phase shift
- Frequency shift
- Can be exploited for condition monitoring

Finite Element Model (FEM)

- Validate experimental measurements
- FRF-based model updating
- ELDV simulation
  - Node resolution
- Damage simulation
  - Element deletion
  - Validation

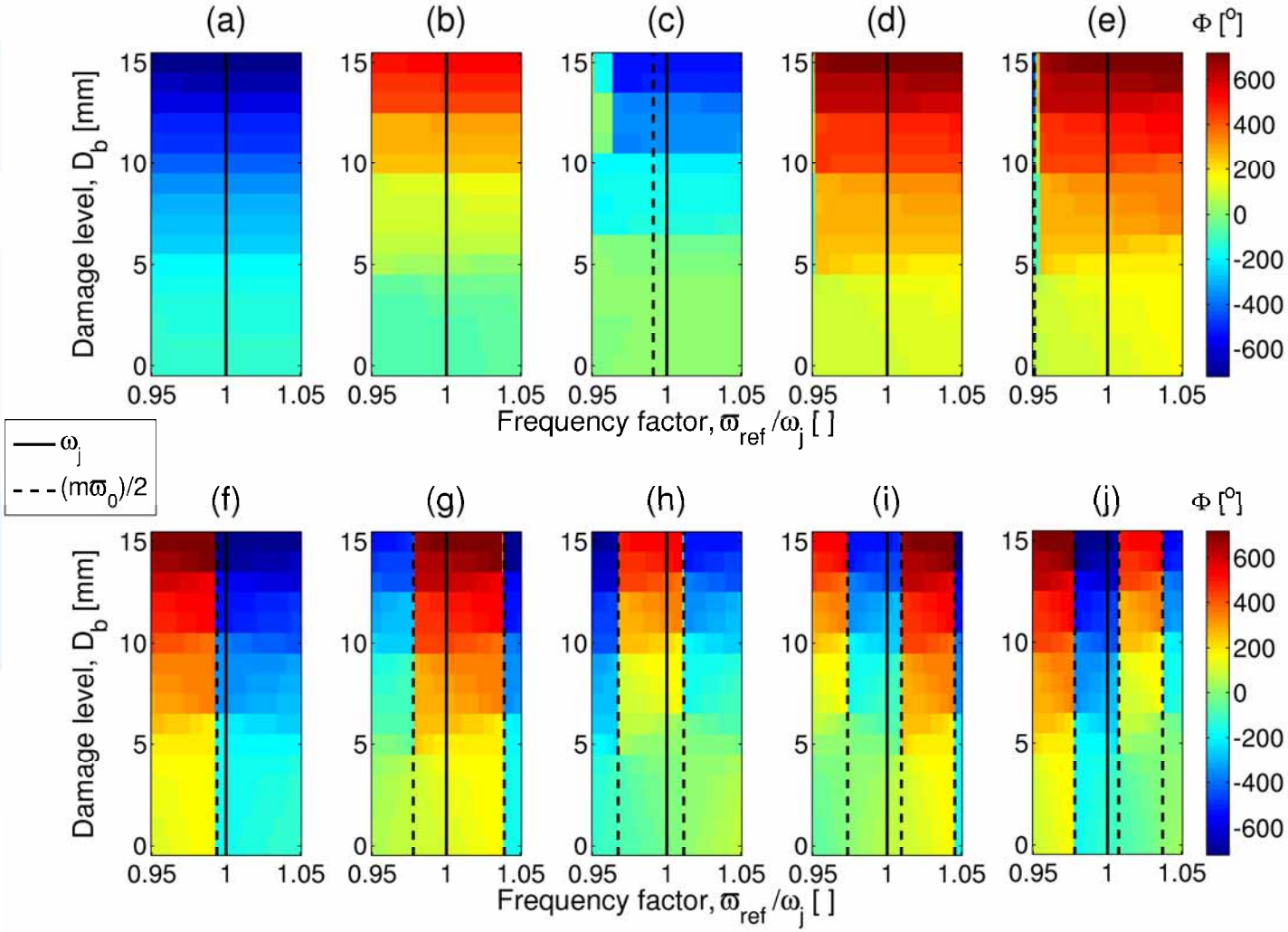


Unwrapped Phase Angle (UPA) trends

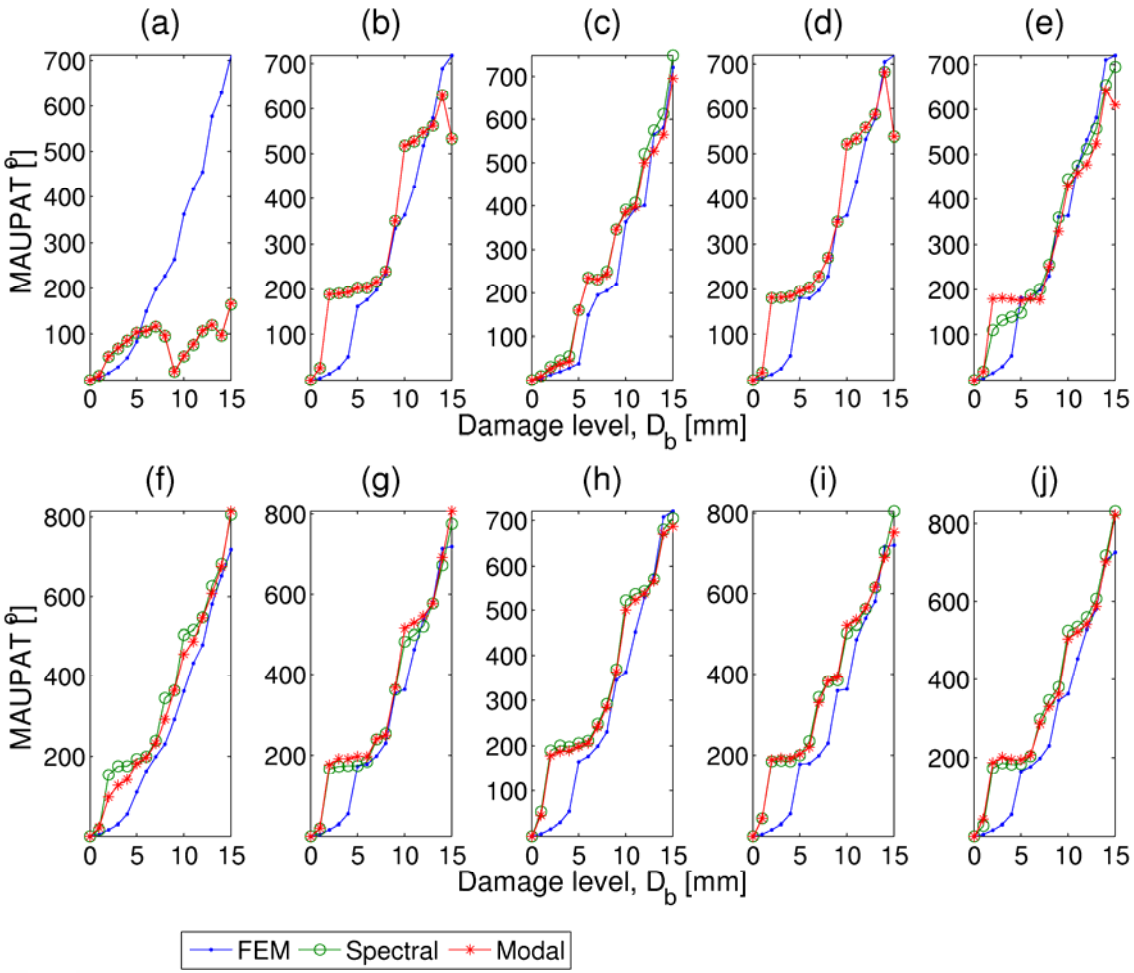


UPA trend sensitivity analysis

Experimental:



Maximum Absolute UPA Trend (MAUPAT)



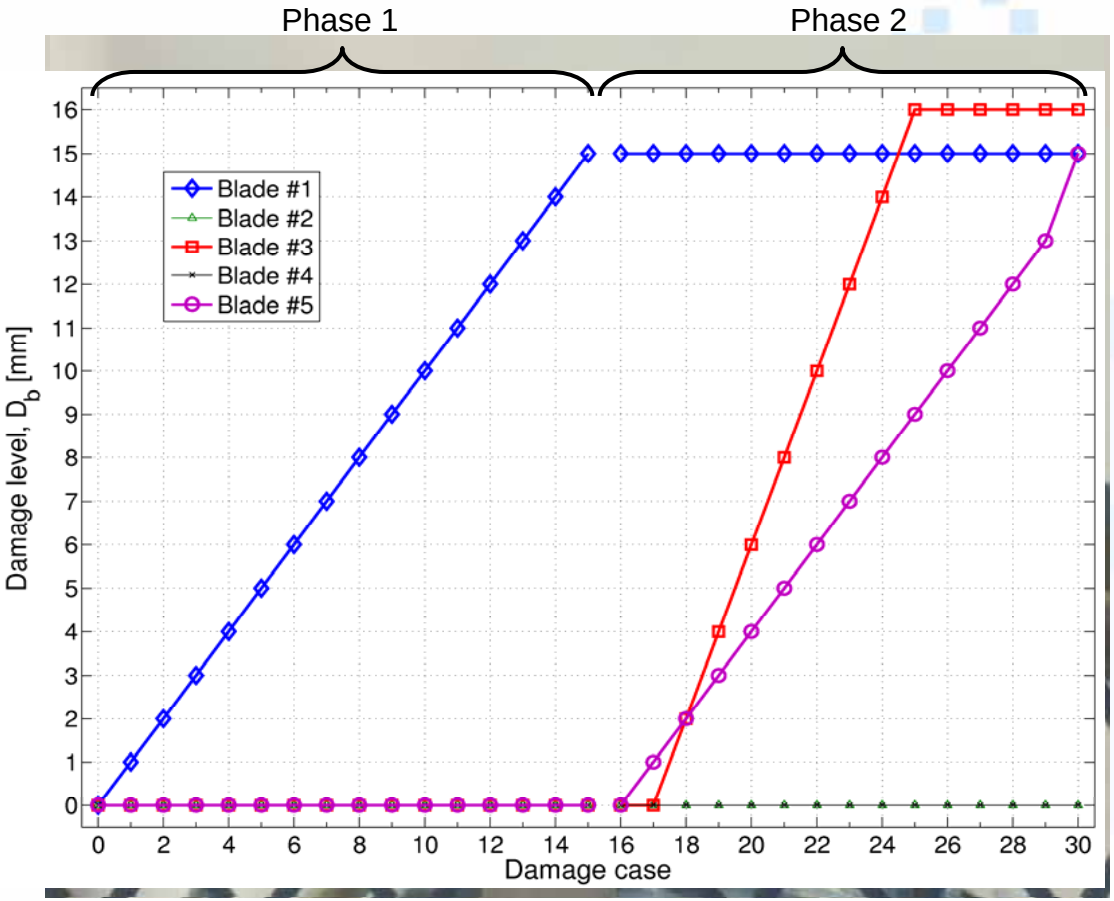
Multi-blade rotor

- 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

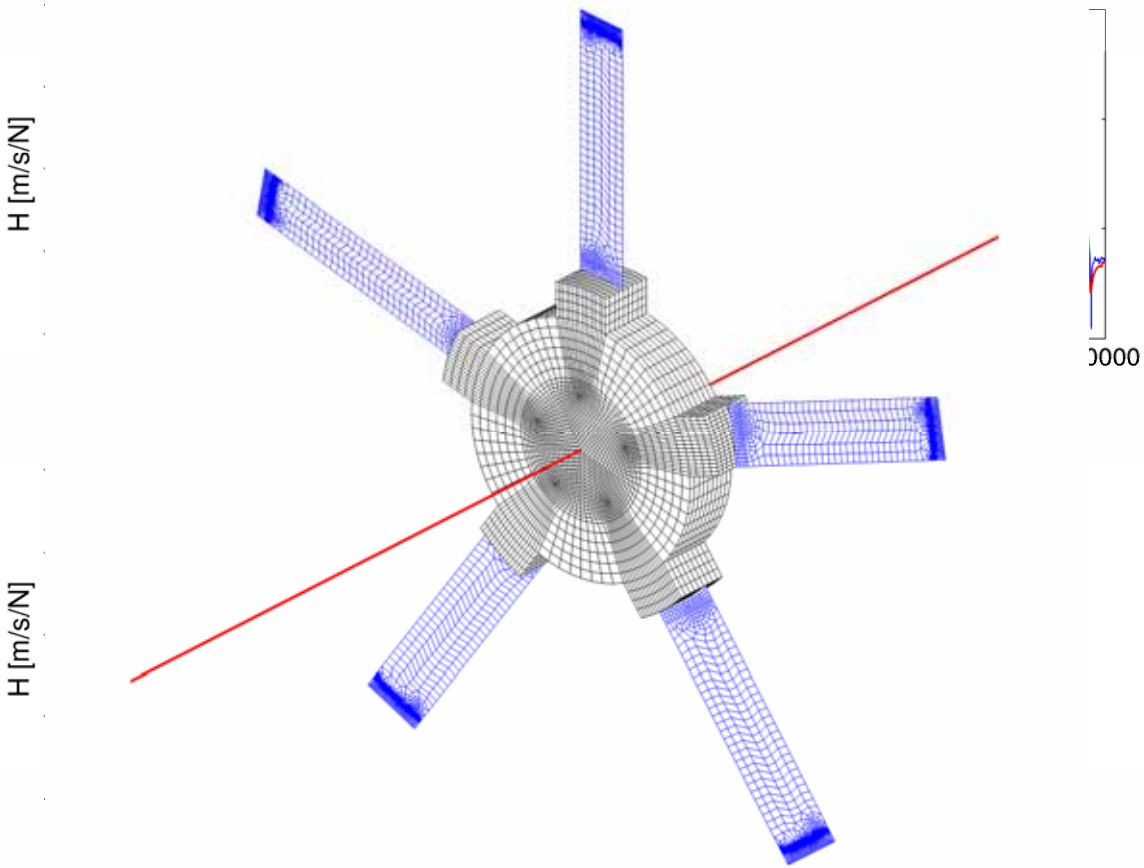
Multi-blade rotor

- Test at various rotor speeds
  - 720, 960, 1200, 1440 RPM
- Multiple blade damage scenarios
- Two ELDV measurement positions
  - Forced
  - Free

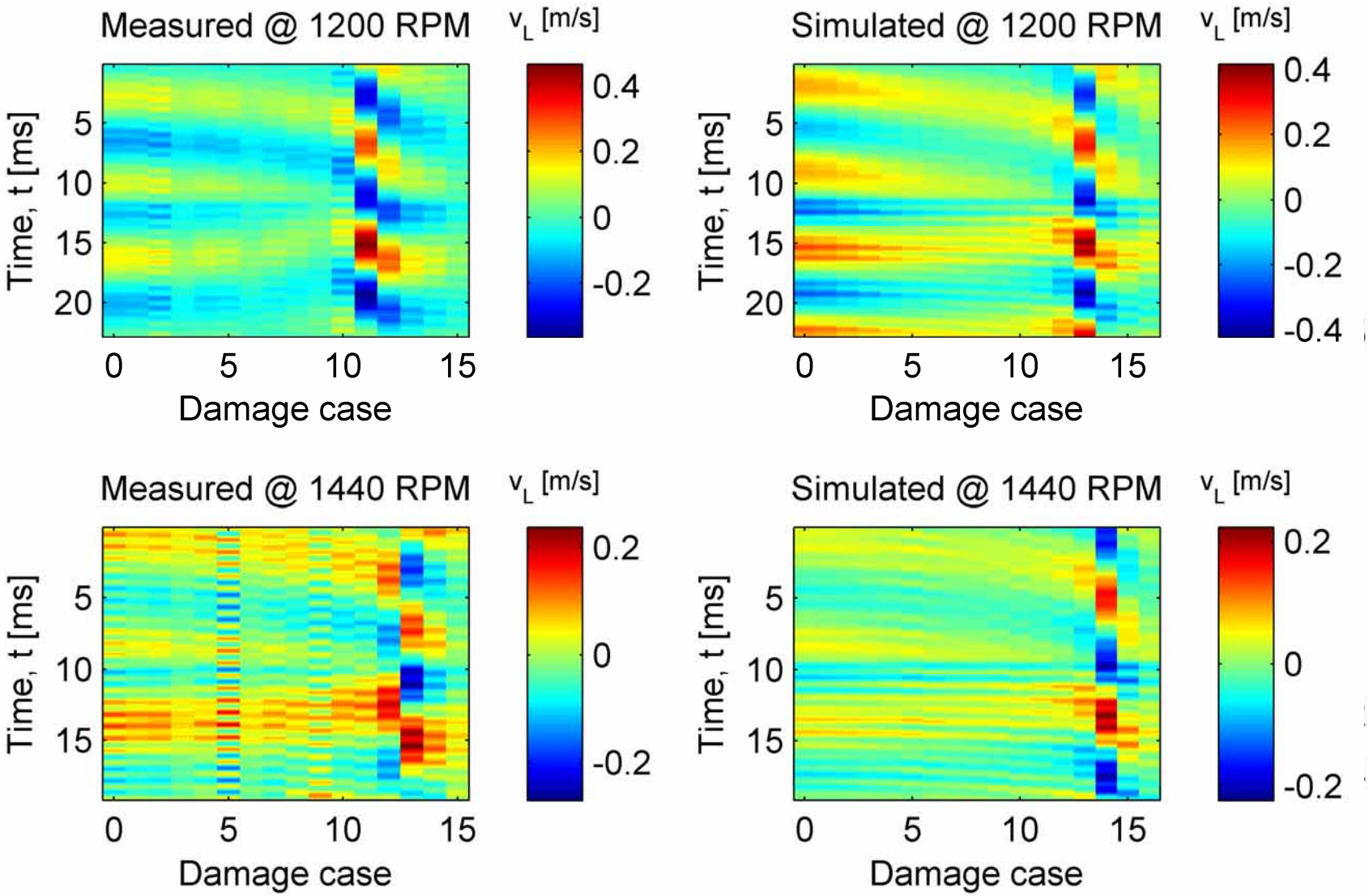


FEM

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

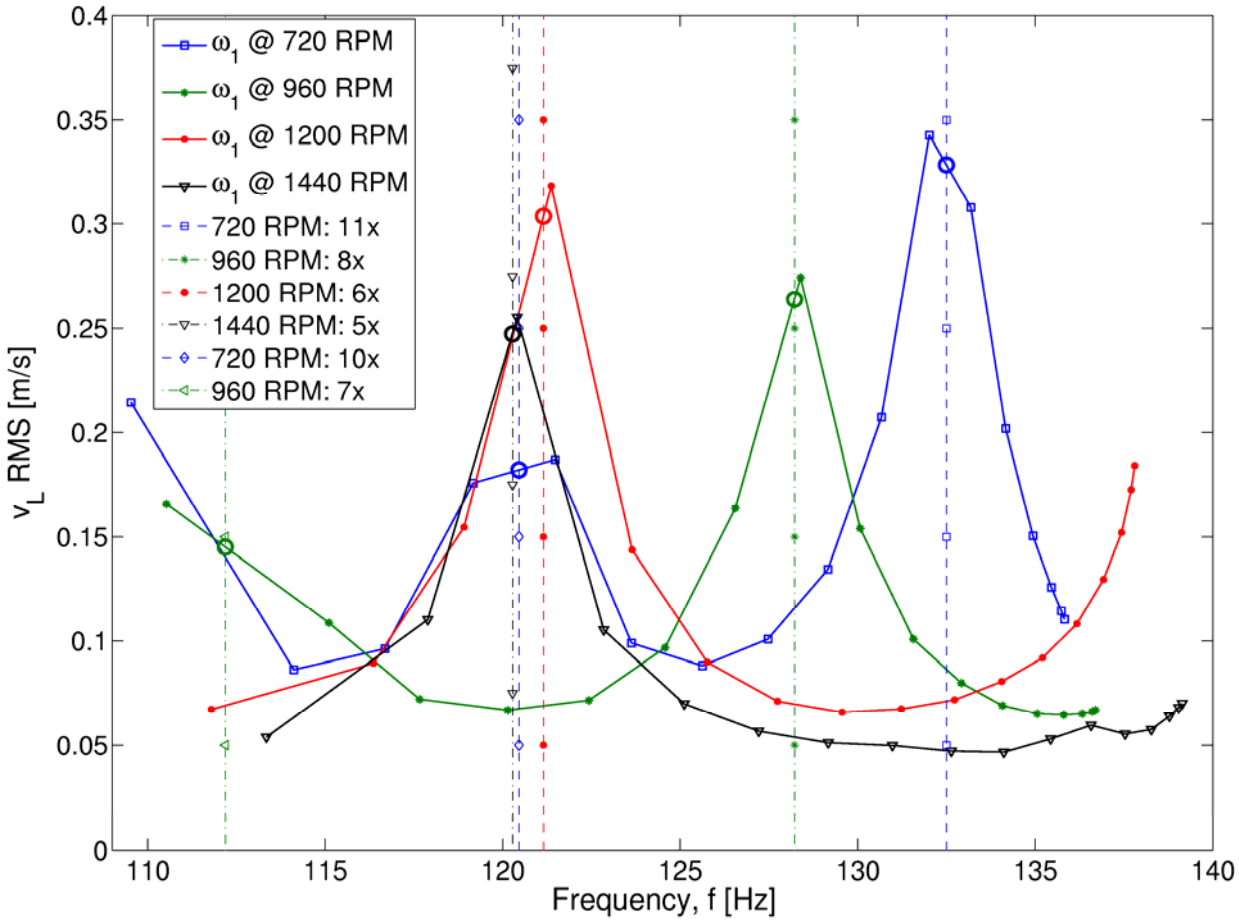


TLDV comparison

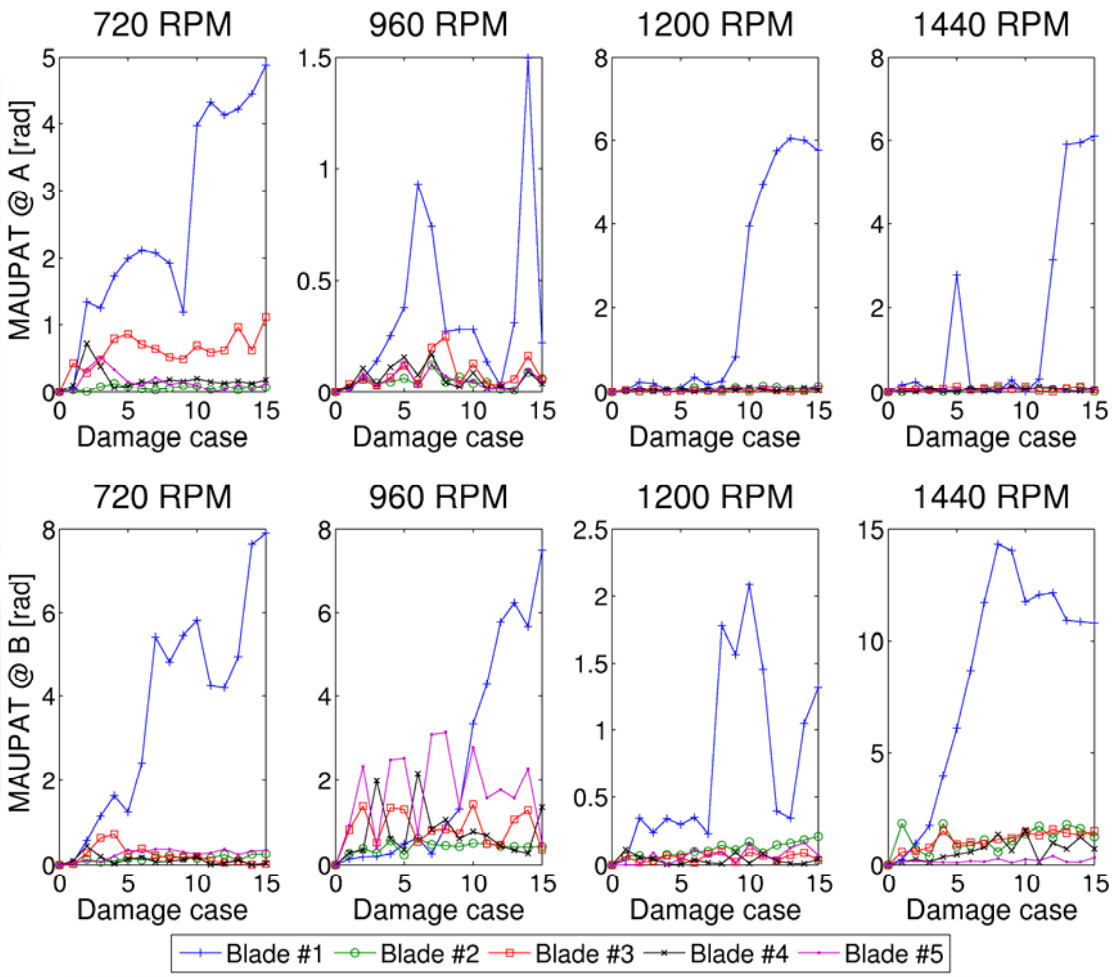


Phase and amplitude irregularities

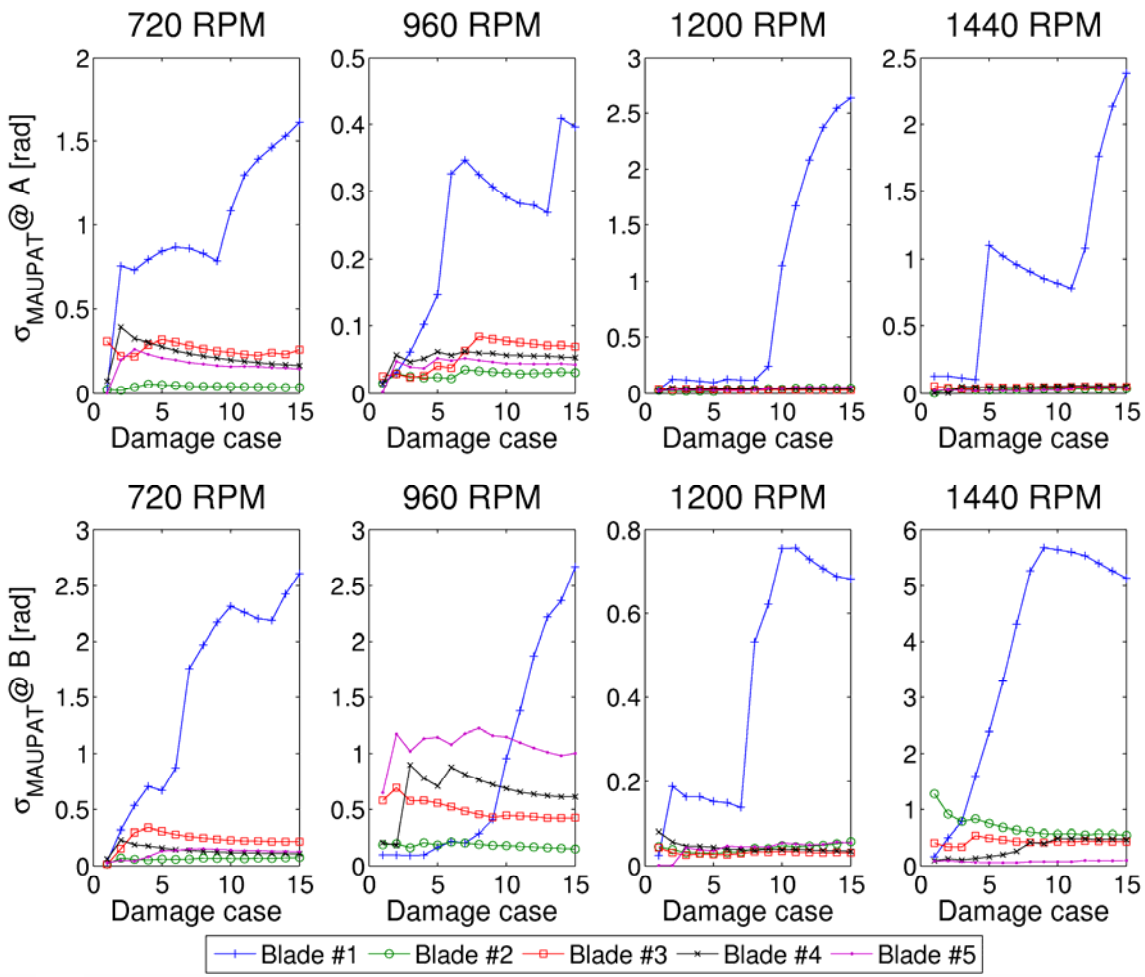
- FEM TLDV
- RMS values
- Blade 1st bending mode natural frequency
- Natural frequency coincides with rotor speed order
- RMS useful as a damage indicator



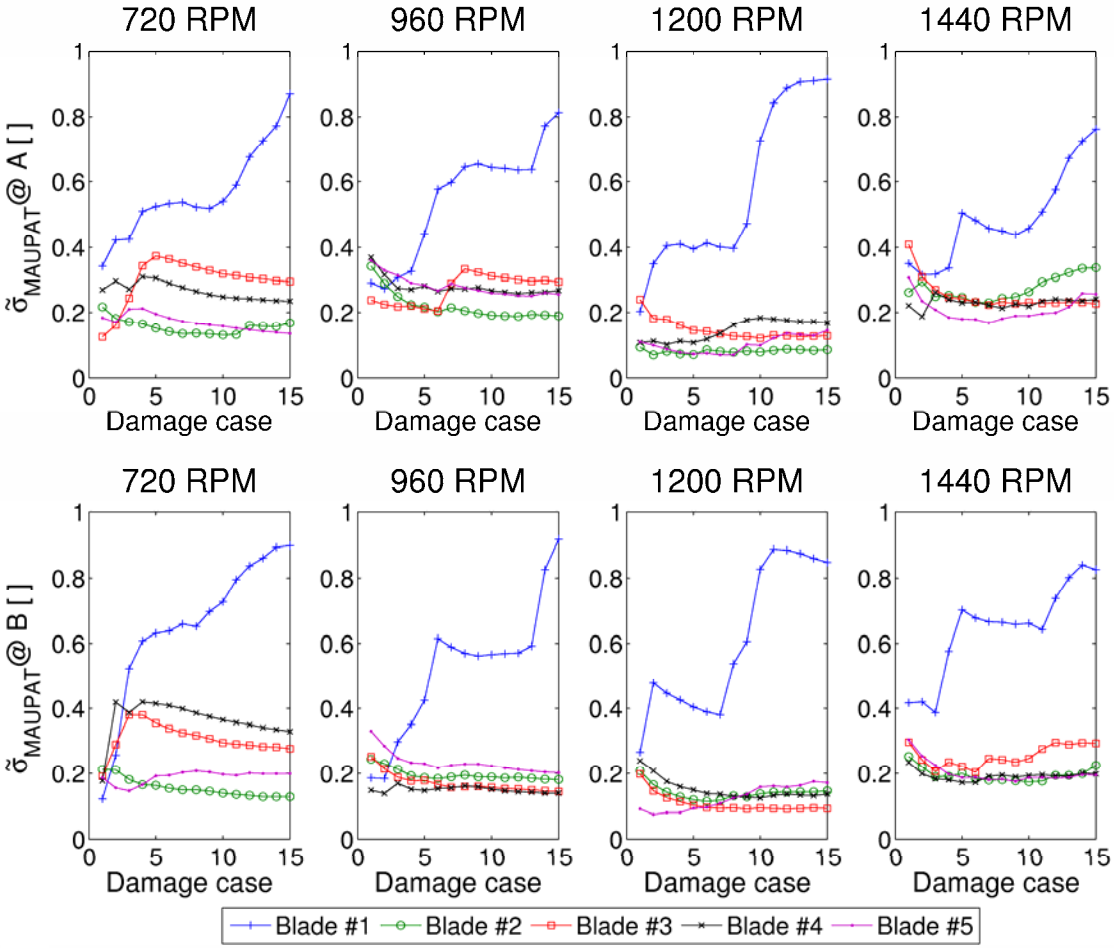
MAUPAT around f_1



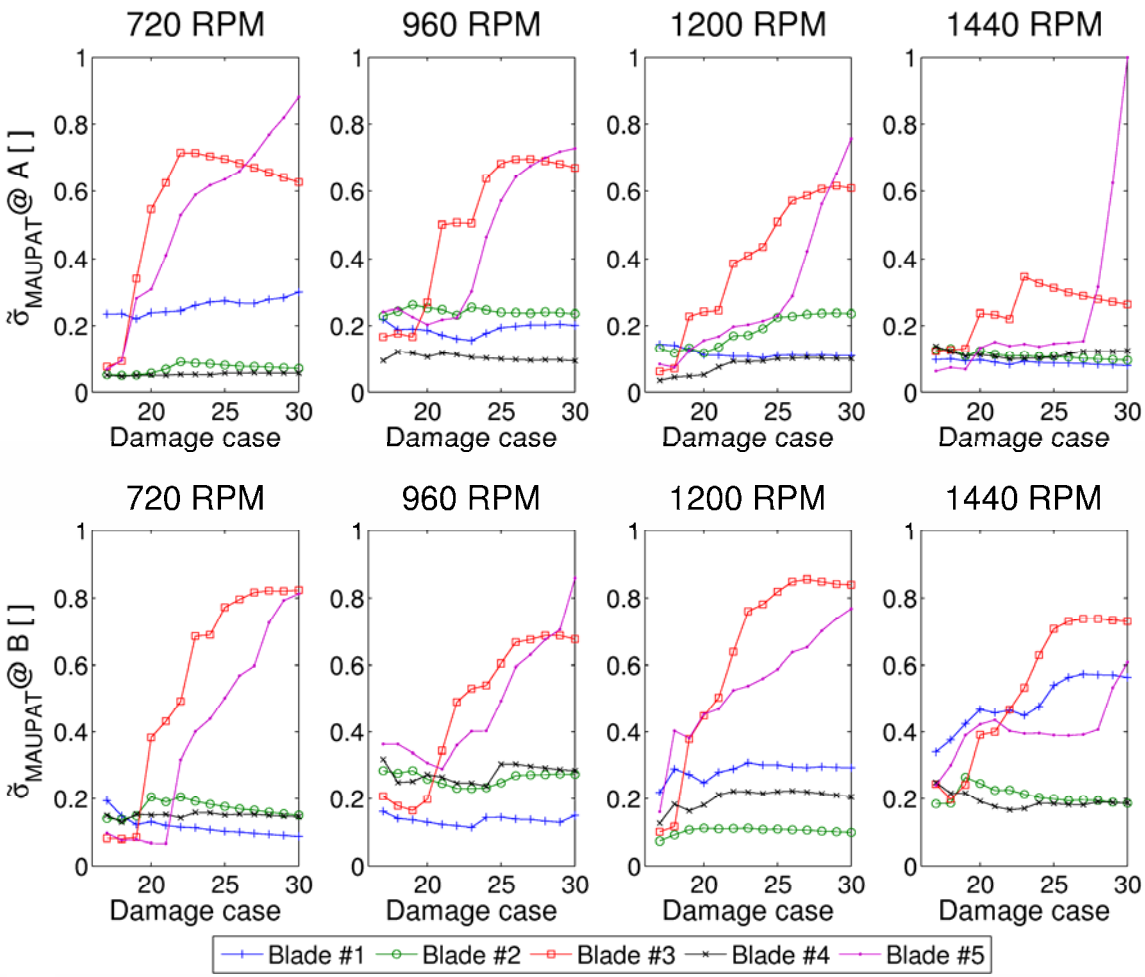
σ_{MAUPAT} around f_1



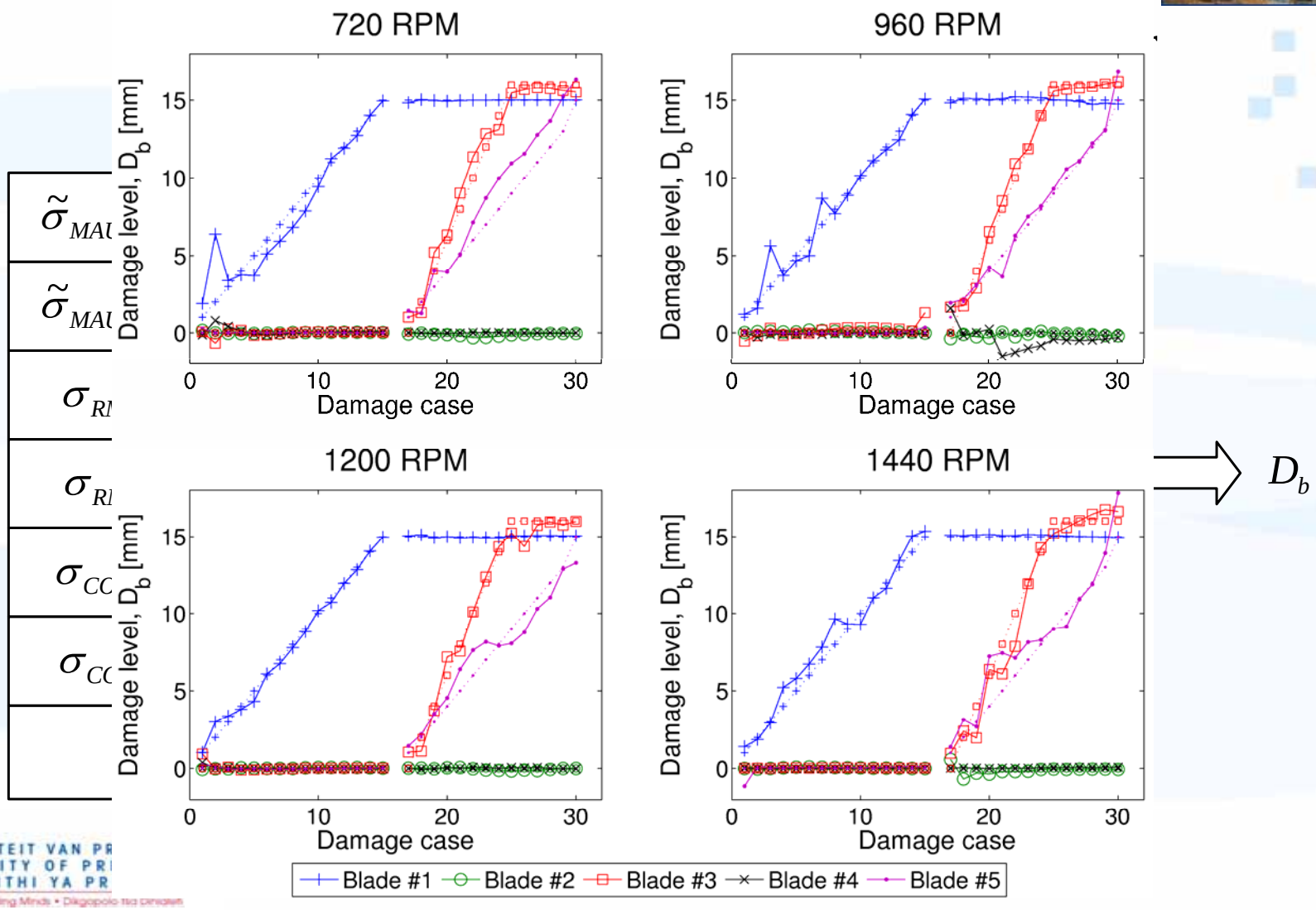
Average σ_{MAUPAT}



Average σ_{MAUPAT} : Multiple blade damage

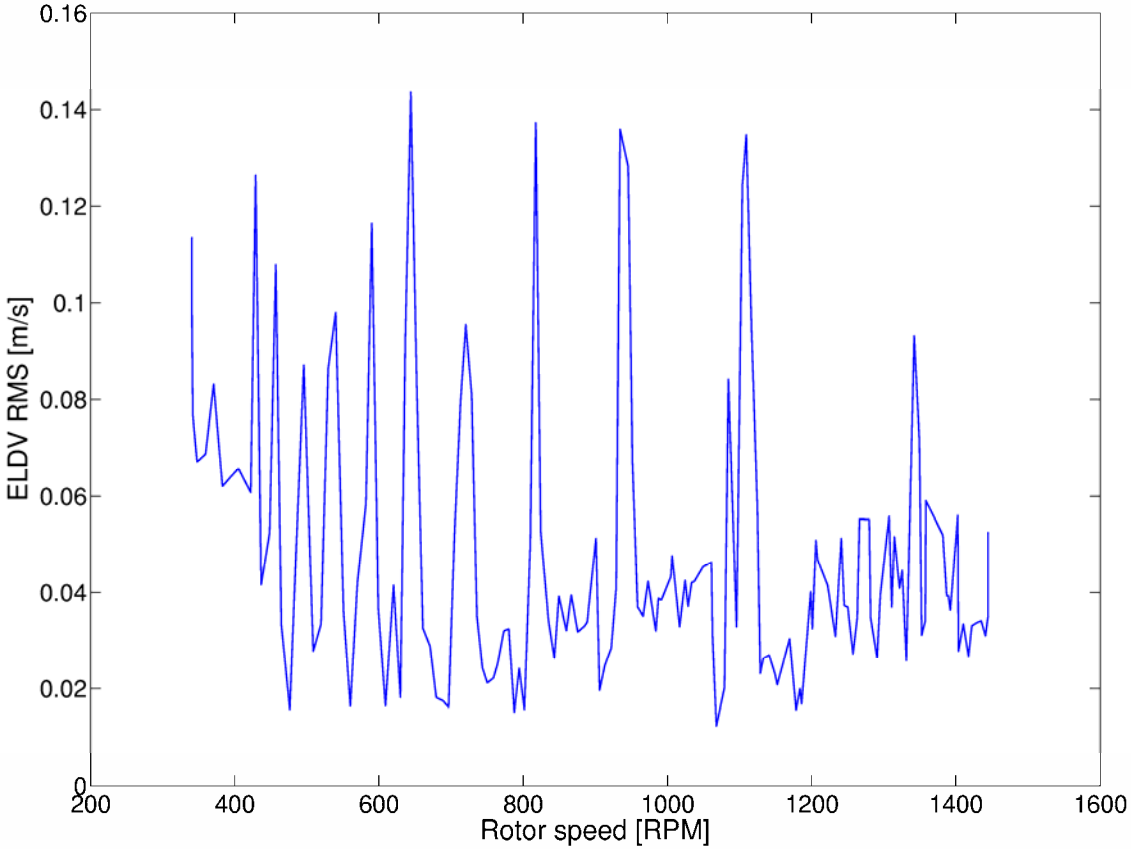


Artificial Neural Network implementation



ELDV natural frequency information

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



ELDV natural frequency estimation

Blade #	FRF frequency [Hz]	Estimated frequency [Hz]	% difference
1	106.25	109.48	3.04
2	137.5	138.11	0.44
3	103.125	105.04	1.89
4	137.5	138.34	0.61
5	109.375	111.64	2.07

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

- Heavenly Father
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- Friends & family

Questions

Thank you!