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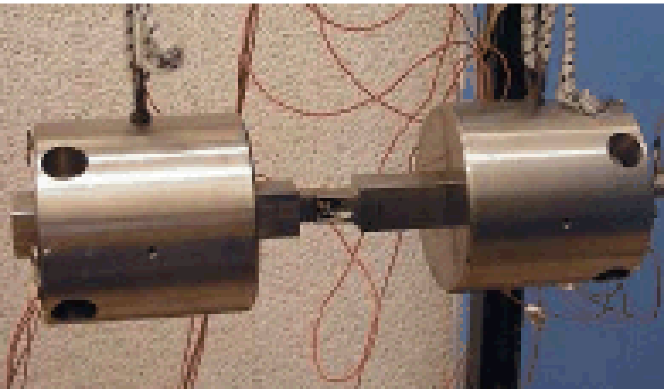

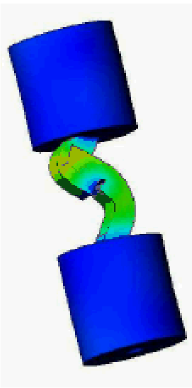

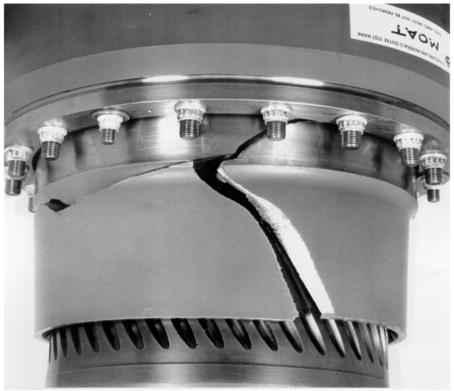

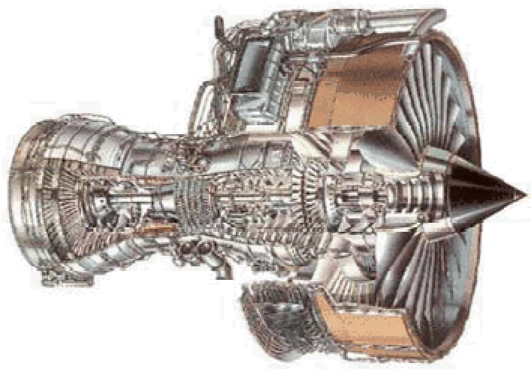

Decoupling Aleatoric and Epistemic Uncertainty

Matt Bonney, Chiara Gastaldi, Brett Robertson, Matt Brake

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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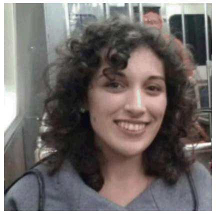
Outline

- Background
- Ampair 600 Wind Turbine
  - Experiments Performed
  - Maximum Entropy Approach
  - IWAN implementation in FEM
- IWAN Uncertainty
- Acknowledgments

Background

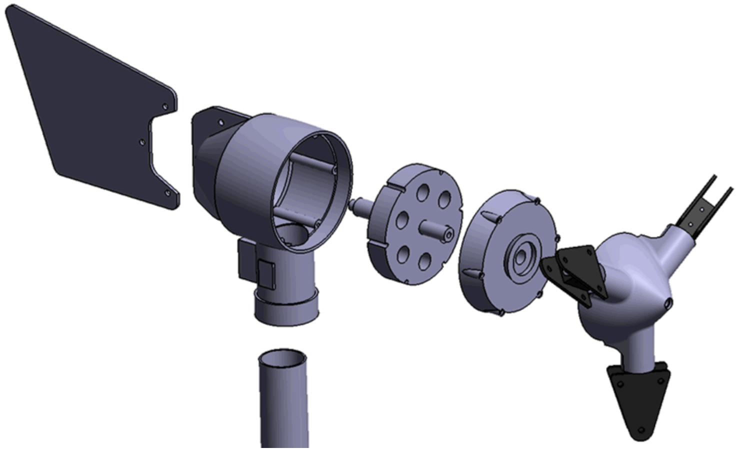


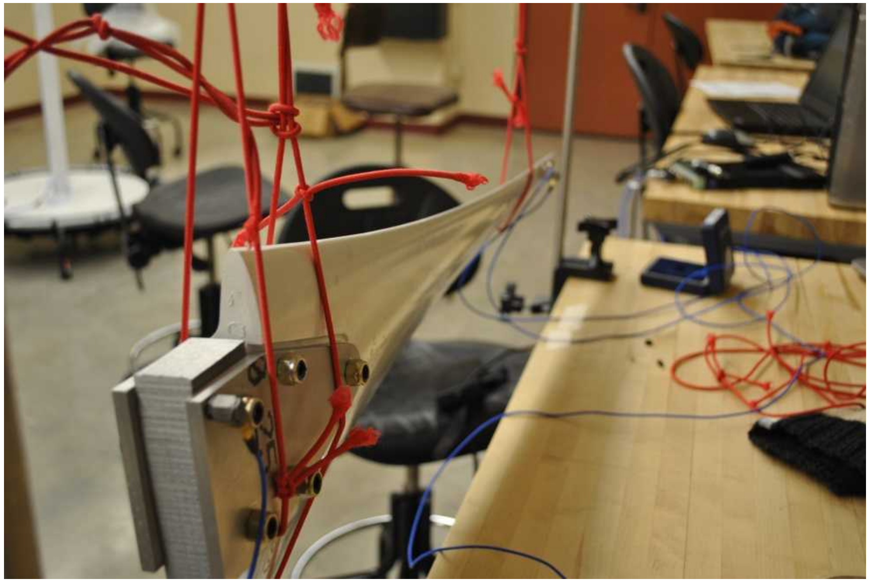
- Personal Biography
  - Chiara Gastaldi : Ph.D. student in Aerospace Engineering at Politecnico di Torino, Advisor: Prof. Muzio M. Gola
  - Matt Bonney : Ph.D. student in Engineering Mechanics at The University of Wisconsin-Madison, Advisor : Dr. Dan Kammer
  - Brett Robertson : Ph.D. student in Mechanical Engineering at Arizona State University, Advisor: Dr. Marc Mignolet

- Ampair 600 Wind Turbine
  - Relatively inexpensive
  - Contains many joints for non-linear analysis
  - Already being used for substructure research, both analytical and experimental

Wind Turbine Model

- Model made by Stuttgart
- Available on Substructuring Wiki page
  - Substructure.engr.wisc.edu
- Website contains both experimental data along with FE data
- Contributors from 8 different universities and organizations





Photos curtesy of substructure wiki

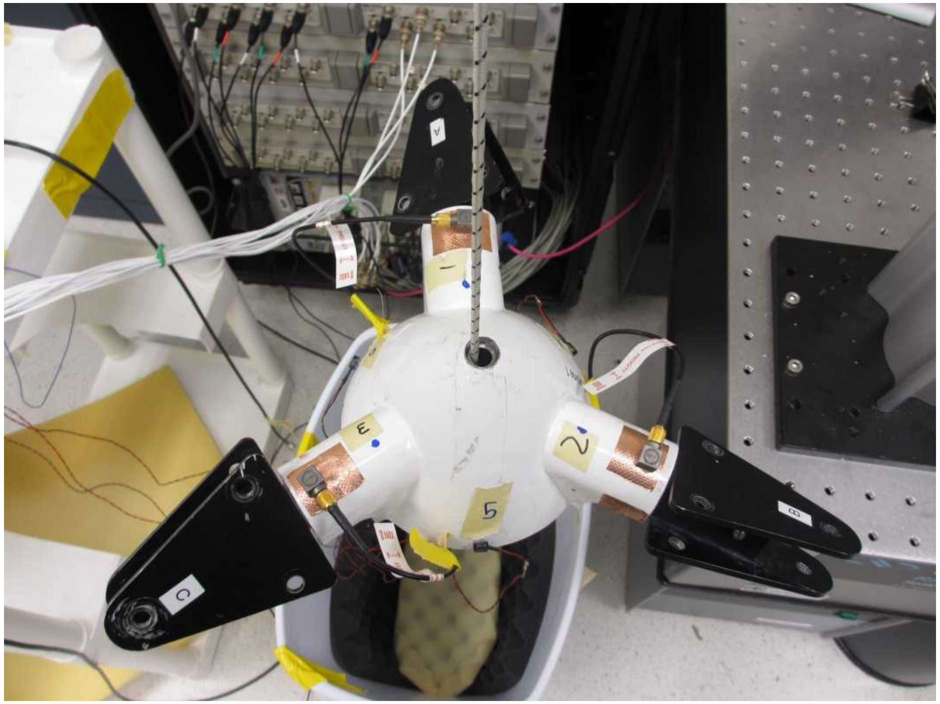
Additional Test: Hub Only

- 3 tri-axis/ 3 single-axis accelerometers
- Impact hammer test performed in order to obtain natural frequencies (Hz):

  1 – 800 (disregarded)

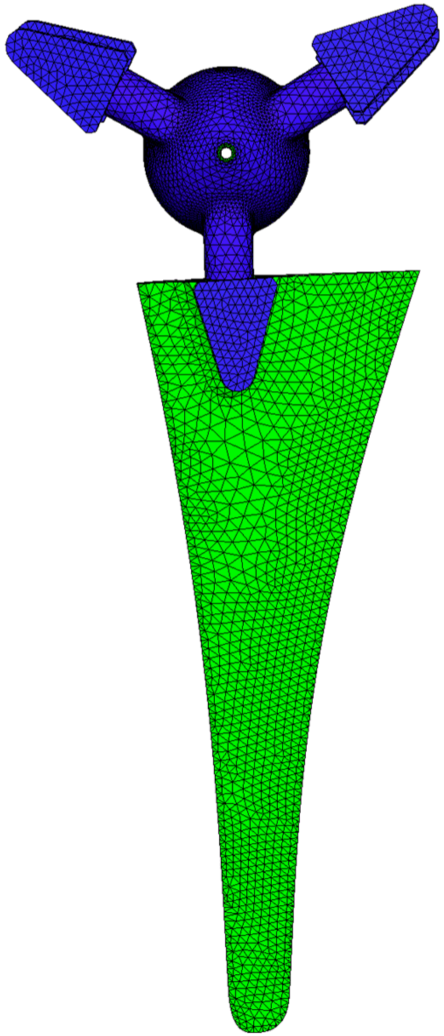
  2 – 1250

  3 – 2300
- Computational model showed several more modes, only calibrated to the second mode (1250 Hz)



Additional Test: Hub and One Blade

- 2 tri-axis accelerometers
- Impact hammer test at different load levels attempting to reveal nonlinearities
- Data showed slight shifts in natural frequencies at low level hits (4, 7 lbf), and up to a 10 Hz shift at a high level hit (45 lbf)
- Results used to validate the discrete Iwan parameters



Maximum Entropy Approach

- Non-Parametric approach
  - Treats parameter uncertainties and model uncertainties independently
- Combination of maximum entropy and random matrices
  - Formulated by Soize[1]
- Uses some experimental data
- Calculates maximum likelihood function for Monte-Carlo solution to determine optimal distribution variables
- Can become computationally expensive but can easily be computed in parallel
- 6 parameter variables, 3 model variables

[1] Soize, C. Maximum entropy approach for modeling random uncertainties in transient analysis, *Journal of the Acoustical Society of America* **109**(5) 1979-1996

Maximum Entropy Results

- Probability density functions for natural frequencies

    » Insert pdfs

Implementing Iwan Element

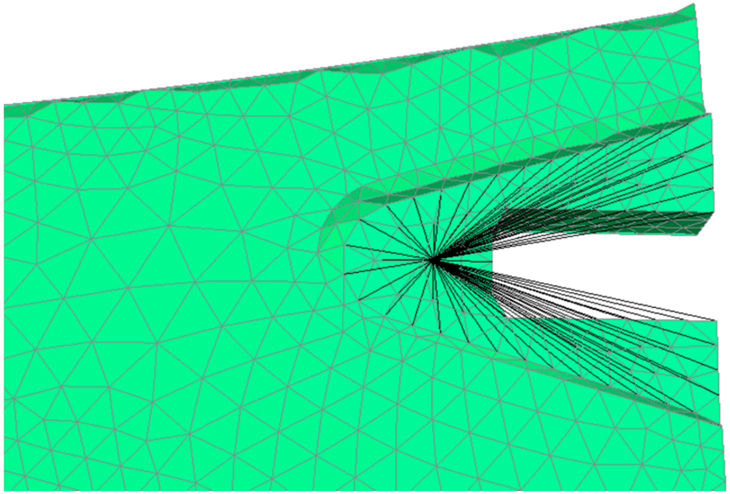
- Joint2g created in Cubit using spiders to connect all nodes to a single point
- Single Iwan for each top and bottom surfaces
- The pair of Iwan elements represent all three bolts in the structure
- Iwan Parameters Used:

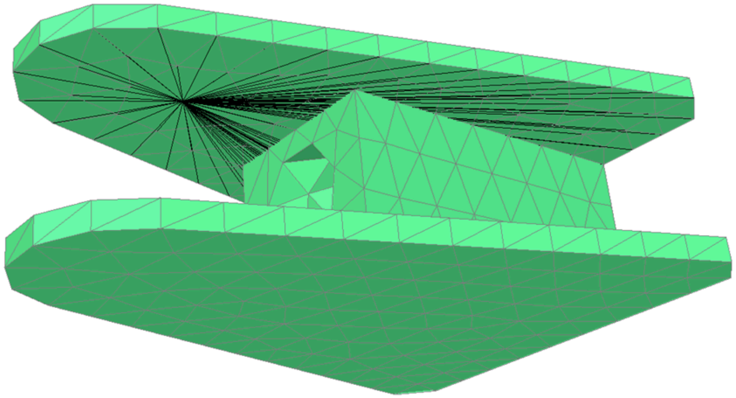
$$\chi = -0.77$$

$$\beta = 0.074$$

$$K_T = 9.825e6$$

$$F_S = 20460$$

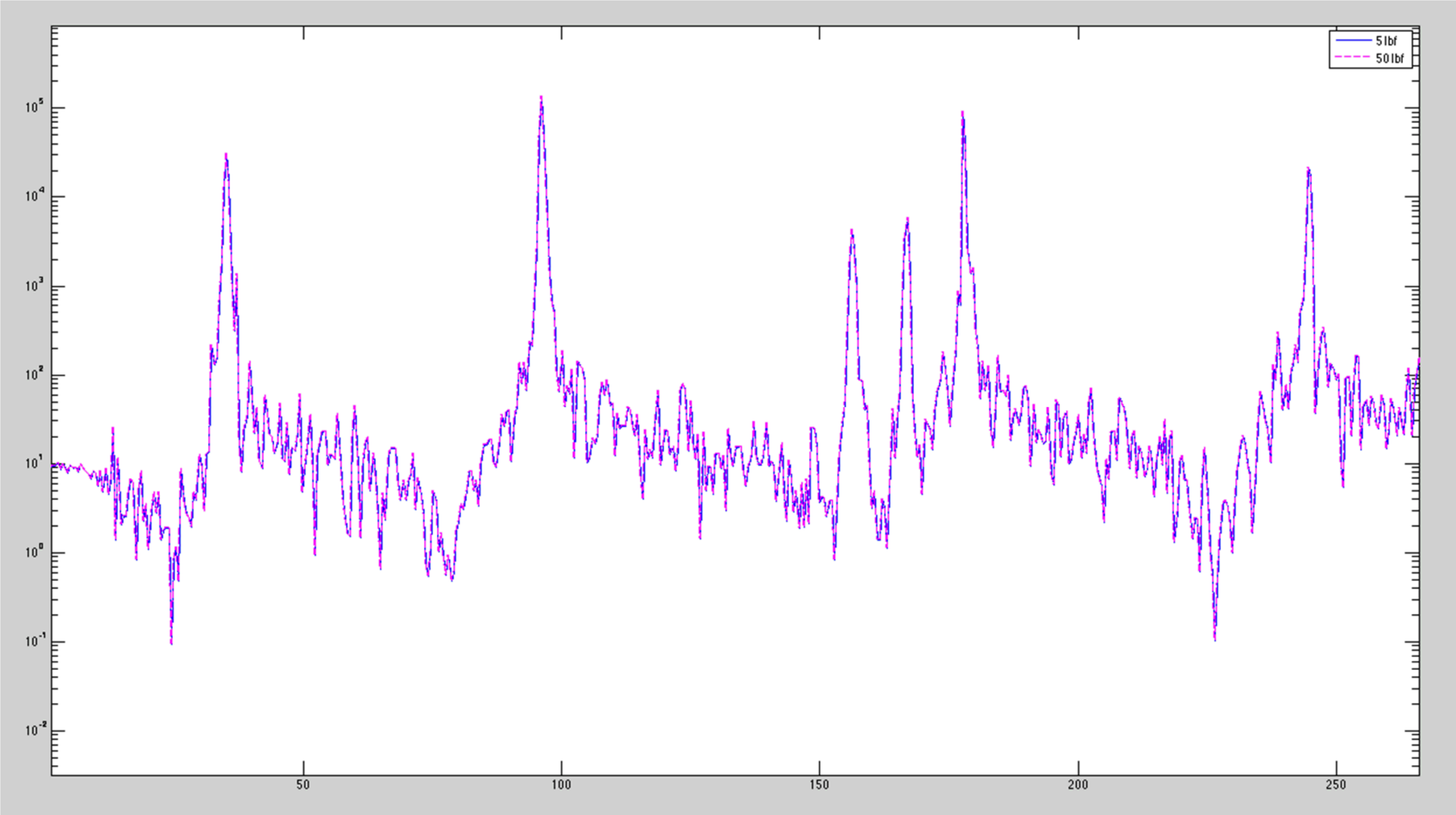




Testing Iwan Using Sierra

- Ran nonlinear transient tests and used experimental data to create the loading function in Sierra, simulating the impact hammer tests
- Applied load to a single node and recorded force and acceleration data at locations both on the flange and the blade
- Use force and acceleration time histories to compute multiple FRF's and see how the natural frequencies respond to different loading levels

Sierra Results Using Iwan



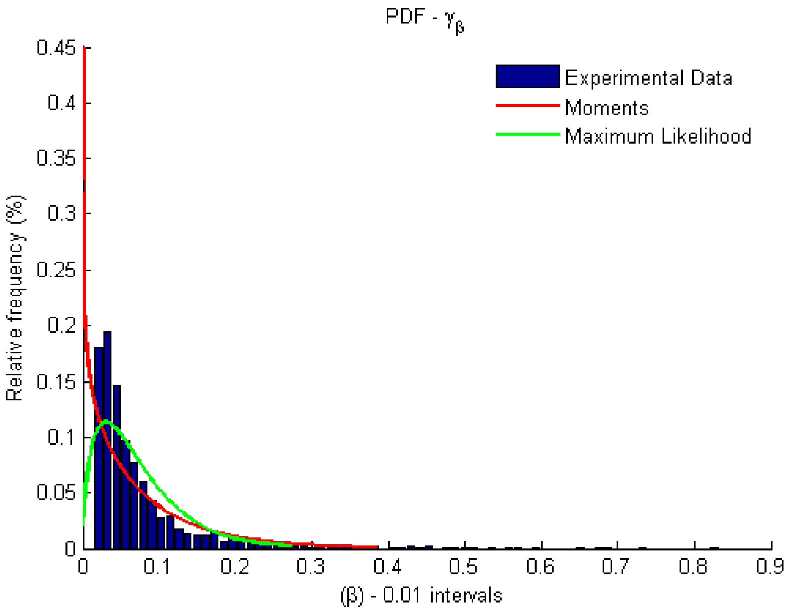
- Linear systems working correctly
- Nonlinear systems having convergence issues

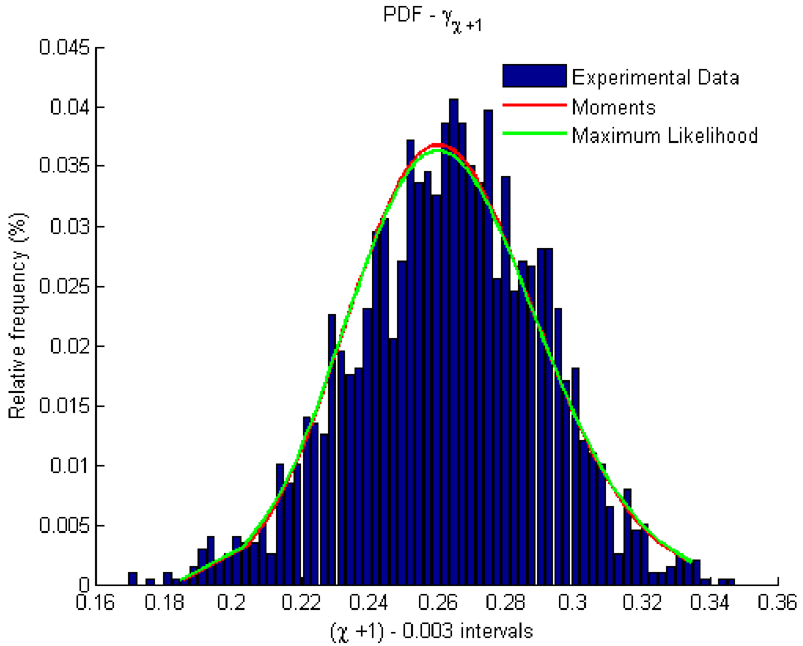
Iwan model – Identifying parameters

For each parameter of the Iwan model a probability density function has been determined parametrically

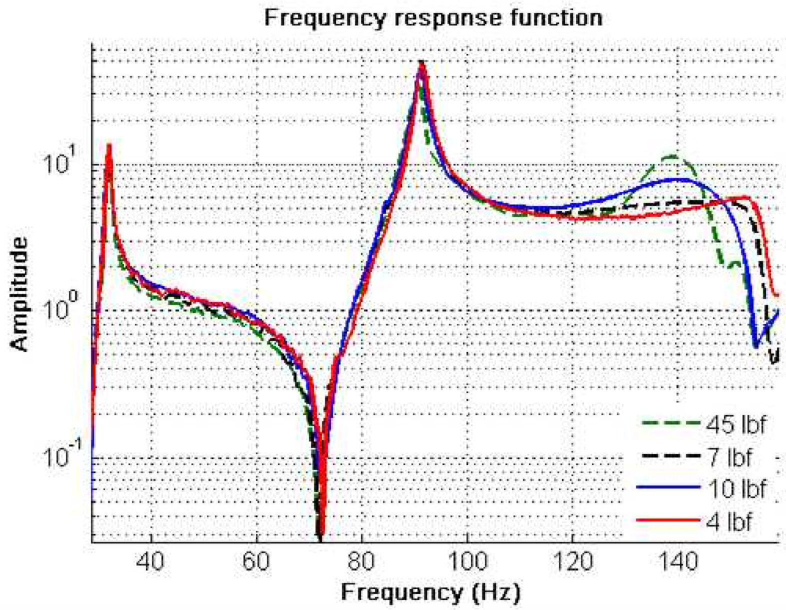
Assumptions:

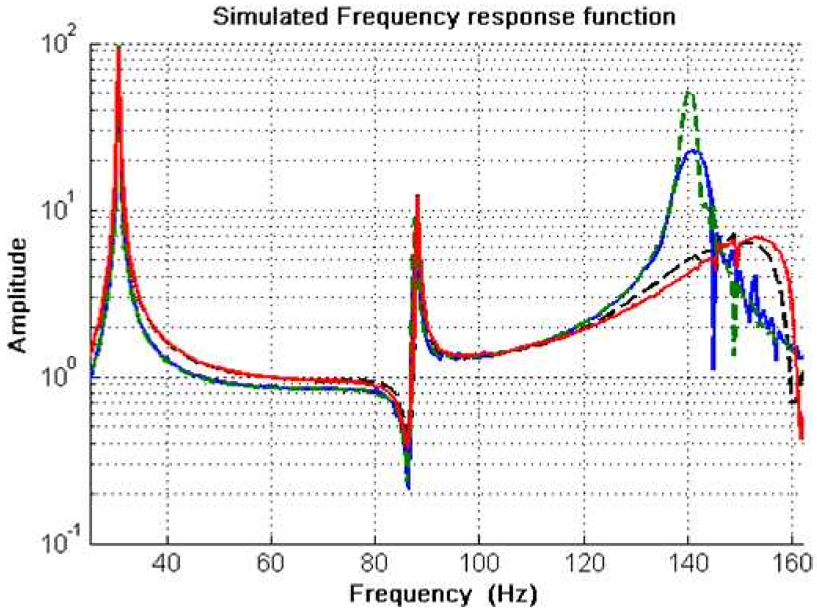
- χ+1,β and K_T PDFs have been estimated using the maximum likelihood approach on the database available on these kind of joints.
- A multiplying factor (2) has been applied to K_T to account for the presence of multiple bolts
- The limiting friction force was assumed to be a uniform distribution, using the nominal clamping force of the bolts and 0.2<μ<0.8

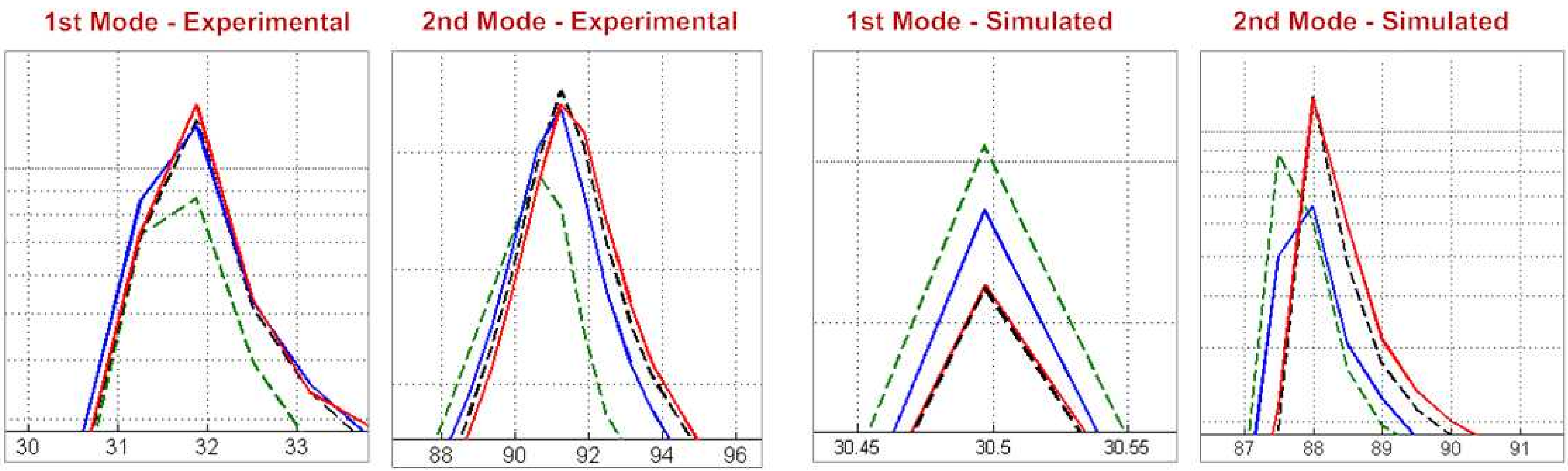




Wind turbine – Academic model



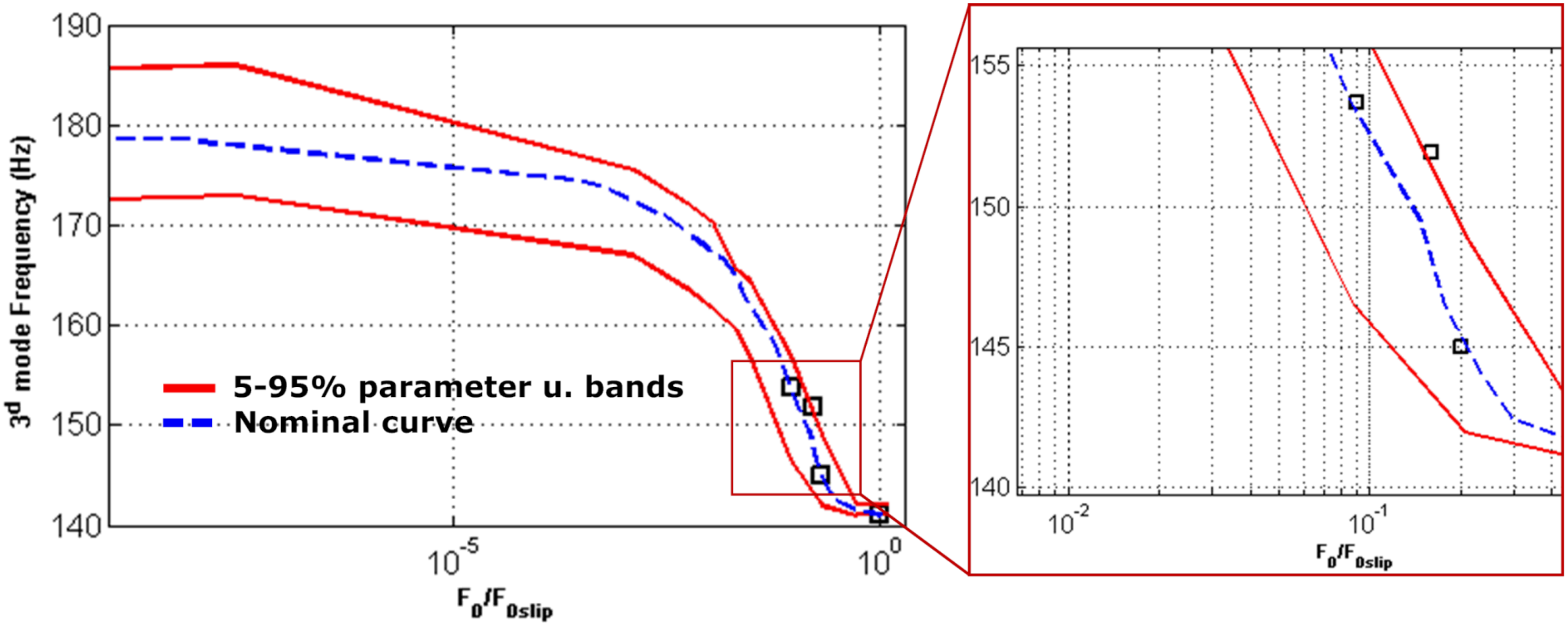




Comparing with Experimental results

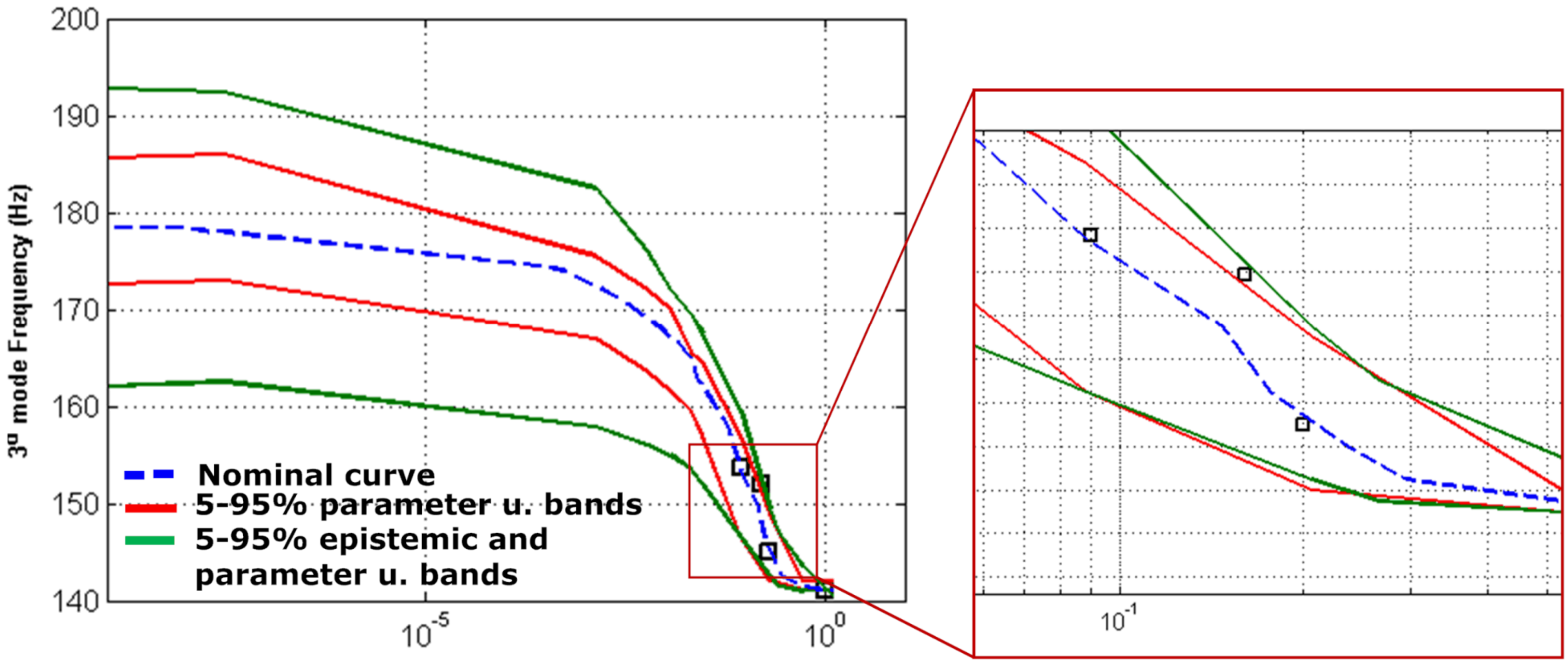
Creating the model

1) Very mild effect of uncertainty bands of the 2nd mode
2) Larger effect of parameter uncertainty on the third mode, which still does not capture all the measurements at different force levels (7 lbf measurement fall out of the band)



Accounting for epistemic uncertainty

- Up to now the stiffness of the jointed interface has been accounted as 2 times that of a single joint
- However the true stiffness may be different: a reasonable assumption is range varying from 1 to 3 times (3 // joints) the stiffness of a single joint.
- The epistemic uncertainty regarding the joints' stiffness is turned into parametric uncertainty -- $K_{Tint} = s \cdot K_{Tbolt}$ where the PDF of s has a uniform distribution

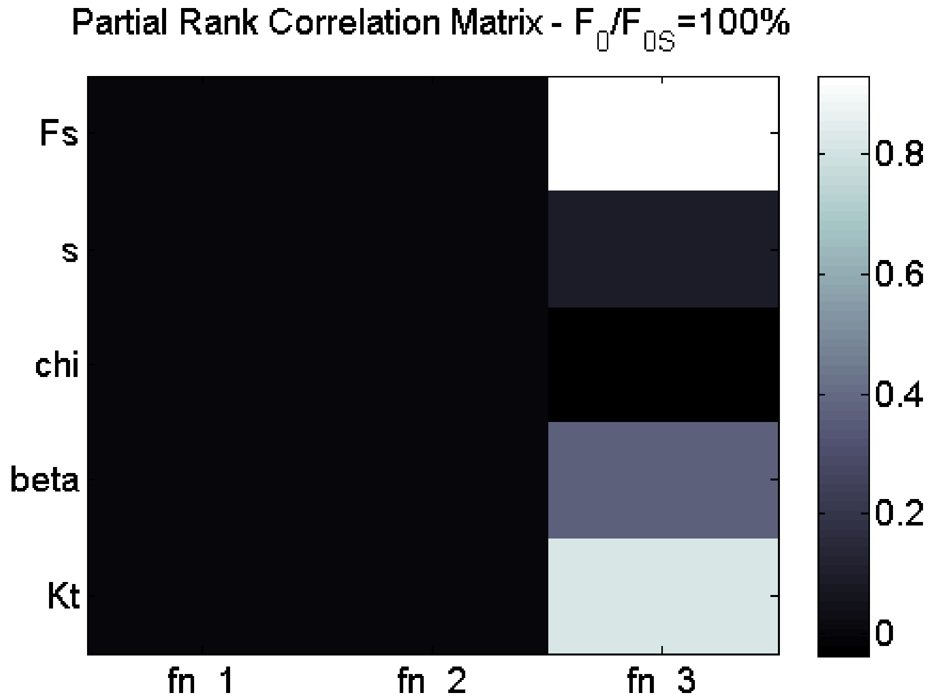


Understanding Iwan – what is important

The non linearity of the model manifest itself even in the behavior of the parameters, and their influence of the relevant output quantities (dependent on the exciting force)

Macroslip regime

- The parameter Fs is the most relevant, since, at this stage, it is the one that can change in a more effective way the slipping condition of the elements
- χ, which accounts for microslip dissipation has no effect at macroslip stage



Acknowledgments

- Matt Brake
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- Matt Allen