Bayesian Updating for Real-Time Crack Detection

Roberto Rocchetta
robertor@liverpool.ac.uk

Supervisors:
Dr. Edoardo Patelli (Engineering)
Dr. Sven Schewe (Computer science)
Dr. Broggi Matteo (Engineering)

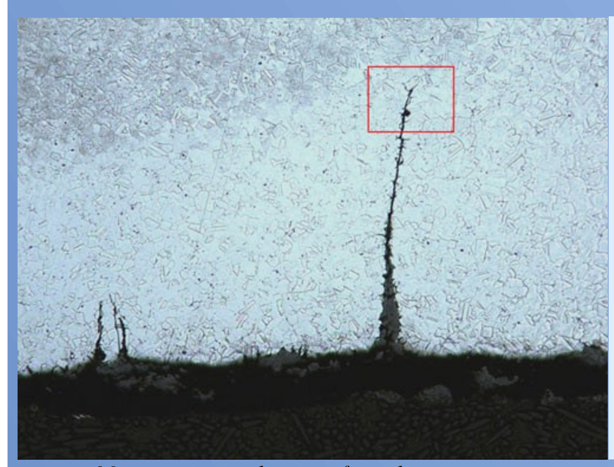
Academic partner:
Professor Enrico Zio
(Ecole central de Paris, and
Politecnico di Milano)

Industrial partner:
European Centre for Soft Computing
(Oviedo, Spain)

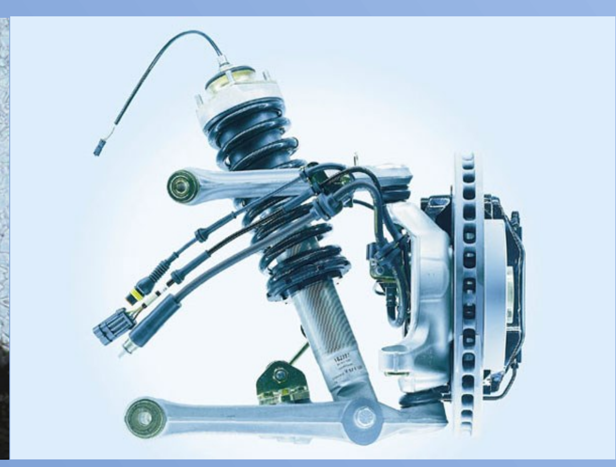
Centre for Doctoral Training
Quantification and Management of Risk & Uncertainty in Complex Systems & Environments

Abstract:

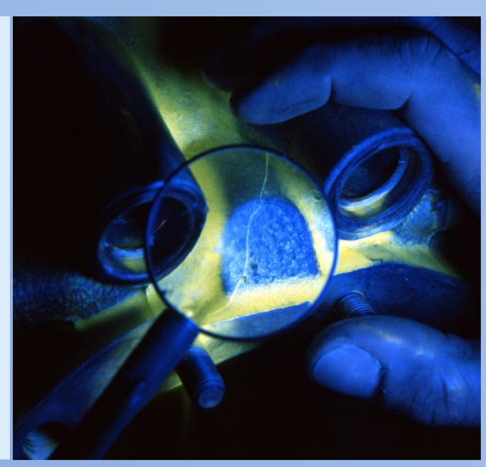
Fatigue is the most dangerous failure mode for mechanical components subject to alternating loads. Due to repeated loading and unloading, one or several cracks can be initiated and propagated through the cross section of the structure. Once a critical crack length is exceeded, fracture may occur and the structure will catastrophically fail even for stress level much lower than the design stress limit. Non-destructive inspections may be performed at predetermined time intervals in order to detect the cracks (e.g. Magnetic particle inspections, ultrasonic inspection). Continuous monitoring of the dynamic response of the structure can allow real-time cracks detection and corrective maintenance procedures might be taken in case the monitoring procedure identifies a crack. In the proposed work, Bayesian model updating procedures is adopted for the detection of crack location and length on a suspension arm, normally used by automotive industry and subject to fatigue stress. Experimental data of the damaged structure (frequency response function) are simulated using a high-fidelity numerical finite element (FE) model of the arm. Surrogate models have been calibrated and selected based on their capability of represent the FE results. The idea underlining the approach is to identify the most probable model consistent with the observations. The likelihood is the key mathematical formulation to include the experimental knowledge in the updating of the probabilistic model. Three empirical likelihood functions have considered and results compared to verify the capability of Bayesian procedure in monitoring the system health state.



Microscopic visualization of cracks

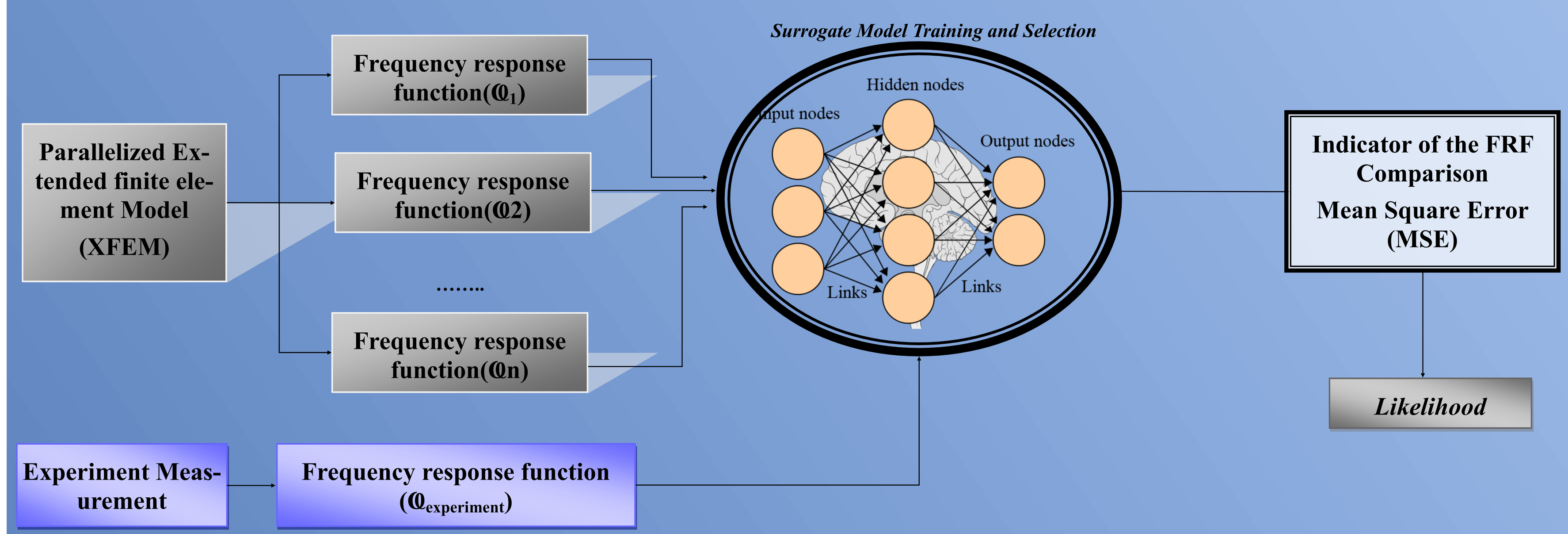


A Mechanical system subject to fatigue



Example of Dye Penetrant Non Destructive Inspection

Diagram of the Parallelization and Meta-Model Strategy for computational time reduction:



1) Objective:

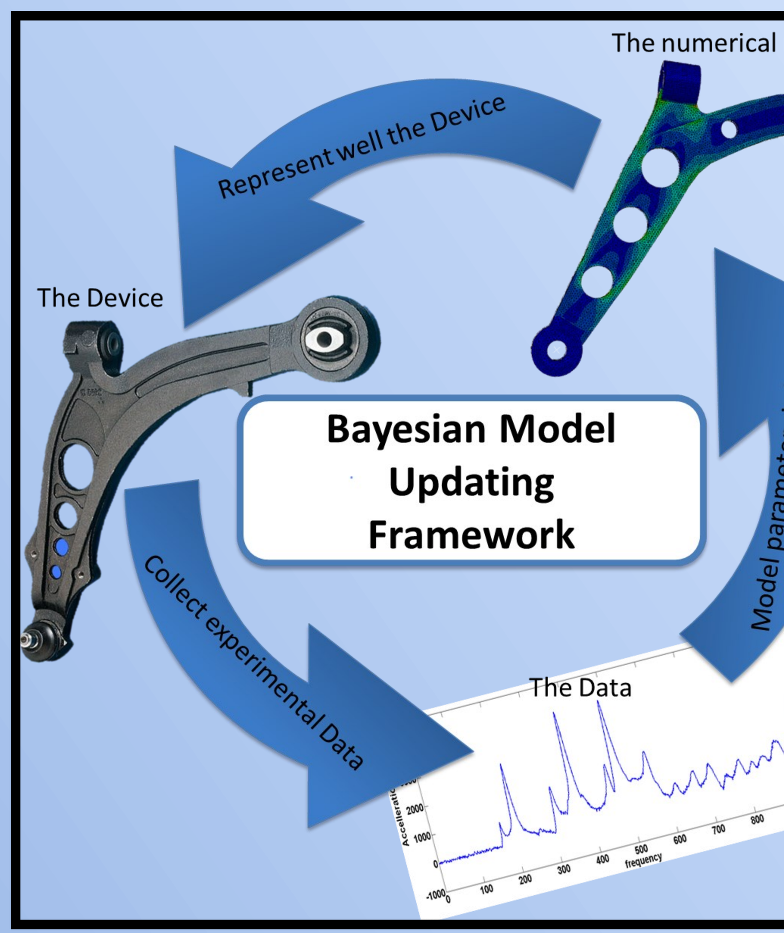
- Framework for real-time identification of cracks in mechanical components subject to fatigue;

2) Challenges:

- Evaluation of the posterior distribution given the observed data, exploration of different empirical likelihood functions;
- Computational tractability to meet Real-Time detection requirement;
- Account for aleatory and epistemic uncertainty

3) Proposed Methodology:

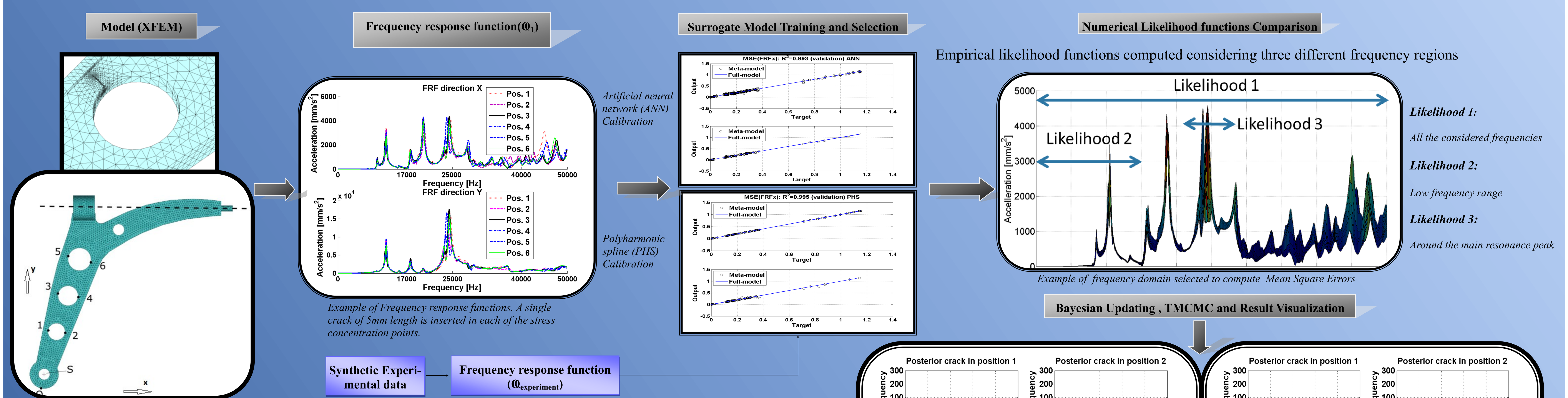
- Bayesian Model Updating and to estimate probability distribution function of the crack parameters;
- Effective Transitional Markov Chain Monte Carlo (TMCMC) ;
- Extended Finite Element Model (XFEM) for crack modelling and solver parallelization on a computer cluster;
- Surrogate Model selection to best mimic the XFEM results and further reduce computational time, which is a strong constraint for real time application.
- Ad-hoc Likelihoods Expression, to account different frequency domain of the Frequency Response Function (FRF);



An illustrative example of the Bayesian Model Updating Framework

4) Case Study and Preliminary Results:

The analysed mechanical component is a suspension arm, similar to those used in the automotive industry. It can freely rotate along the axis indicated by the dashed line; the suspension spring and the wheel structure are connected at the location indicated by "S". The stress concentration points, and candidate crack locations, are indicated in the figure by the numbers 1 to 6. A crack with fixed length is inserted in one of the candidate position, and the reference FRF is computed at the position indicated by "O". The crack lengths and positions are considered as uncertain parameters and updated in order to minimize the differences respect to the synthetic measurement of the system to be monitored.

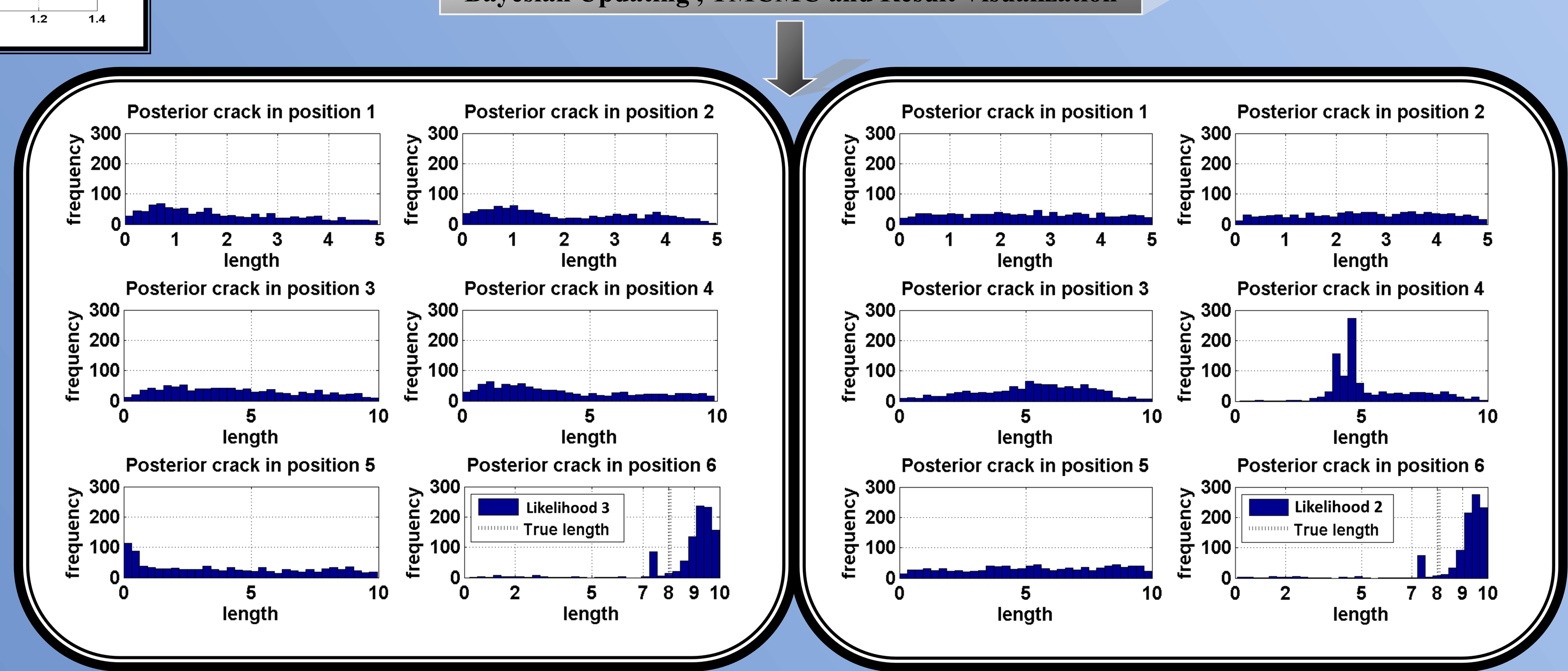


Example of Frequency response functions. A single crack of 5mm length is inserted in each of the stress concentration points.

Example of frequency domain selected to compute Mean Square Errors

On top: re mashing around crack length;
On bottom: the suspension arm FE model, the six possible crack positions and measurement point O;

Bayesian Updating , TMCMC and Result Visualization



Posterior distributions obtained with two different likelihood functions, synthetic experimental data of crack in position 6 of length 8.04 mm,

5)Conclusions and Future developments:

A Bayesian model updating procedure for cracks detection has been applied to detect cracks in a suspension arm. Reference dynamic data from vibration analysis (FRF) was used as target for the updating. The effects of different numerical likelihood expressions and different experimental data on the crack detection strategy have been analysed. The procedure has been tested first to detect a single crack with unknown length but known position, the result comparison did not suggest major differences between the likelihood formulas and the detection procedure appear promisingly precise. Nevertheless, the second case point out the limitations. This is possibly due to similarity in the FRF for different cracks or shortcoming in the computational accuracy. In both the analysed cases, the crack was detect correctly around the true length and position and the computational time have been dramatically reduced. Future development and additional research will be taken by using real experimental data to further validate and expand the proposed approach, furthermore uncertainty in the device parameters will be accounted to increase robustness.

6) Synergic Research directions:

Advanced uncertainty quantification frameworks:
Conference paper: *''A Computational Framework for Classical and Generalized Uncertainty Quantification: Solution to the NAFEMS Challenge Problem''*; R. Rocchetta, M. Broggi, E. Patelli, NAFEMS Conference San Diego 2015

Risk assessment framework of complex systems:
Conference paper: *''Simulation-Based Risk Assessment Framework for Electric Vehicles Strategies Comparison Accounting Renewable Energy Sources''*; R. Rocchetta, E. Patelli IPW conference November 2015

References:

Goller, B., M. Broggi, A. Calvi, & G. Schu¨eller (2011). A stochastic model updating technique for complex aerospace structures. Finite Elements in Analysis and Design 47(7), 739–752.

Bayes, T. (1763). An essay towards solving a problem in the doctrine of chances. Philosophical Transactions of the Royal Society of London 53, 370–418.

Patelli, E., M. Broggi, M. de Angelis, & M. Beer (2014). Opencossan: an efficient open tool for dealing with epistemic and aleatory uncertainties. Vulnerability, Uncertainty, and Risk: Analysis, Modelling, and Management, 2564–2573.

Ching, J. & Y.-C. Chen (2007). Transitional Markov chain Monte Carlo method for bayesian model updating, model class selection, and model averaging. Journal of engineering mechanics133(7), 816–832.

Abdelaziz, Y. & A. Hamouine (2008). A survey of the extended finite element. Computers & Structures 86(11-12), 1141–1151.