Nonlinear System Identification, Reduced Order Modeling, and Model Updating of the Effects of Mechanical Joints on Structural Dynamics

Keywords*:* mechanical joints, nonlinear system identification, finite element model updating

Summary: Mechanical joints are present in nearly every structure, device, or vehicle in operation today. As these become ever more complicated the need for the classification and understanding of the nonlinear effects on structural dynamics grows ever more critical. I propose to apply recently developed nonlinear system identification methods, reduced order modeling and model updating techniques to characterize and model these nonlinear effects. The outcome of this research will be the development of models for use in standard finite element (FE) methods that capture the nonlinear effects of mechanical joints.

Literature Review: Several techniques exist for the identification of joint parameters, but these methods require extensive instrumentation and measurements that may not be practical and rely on frequency response functions that are assumed to be linear [1]. Yet the current FE model updating techniques necessitate accurate modal parameters and often produce results that differ greatly from experimental results [1]. A recently developed nonlinear analysis methodology with broad applicability can be applied to alleviate these issues by characterizing the nonlinearities and developing reduced order models for use in standard FE codes.

The proposed method relies on the assumption that the application of Empirical Mode Decomposition [2], a time-domain based signal decomposition method, results in nearly orthogonal components, called Intrinsic Modal Functions (IMF), characterized by ‘fast’ oscillations controlled by ‘slow’ changing amplitudes [3-5]. The IMFs result in local nonlinear interaction models [6] that portray the local dynamics through sets of intrinsic modal oscillators (IMO). The IMOs are able to reproduce the measured times series while completely capturing the effects of the nonlinearities.

The global dynamics are determined by superimposing the wavelet transform (WT) of the original time series in the energy-frequency domain with the frequency-energy plot (FEP) [7] of the representative Hamiltonian system. By assessing the global dynamics an understanding of the energy dependence of the nonlinear normal modes [7] of the system can be developed. This method was recently applied to a beam with a bolted lap joint to identify the damping nonlinearities and the effects on the structural dynamics [8]. This research aims to continue that study and extend the results into FE model updating.

Hypothesis: Through the application of recently developed nonlinear system identification, reduced order modeling, and model updating techniques the nonlinear effects of mechanical joints on structural dynamics can be classified and incorporated into standard FE models.

Research Method: In order to study the effects of mechanical joints, steel beams will be constructed that incorporate bolted, riveted, and welded connections. “Monolithic” steel beams without any connections, but with holes, bolts, rivets, etc. will be used as experimental control beams for the analysis. The beams will be constrained in various positions to model the most common structures: cantilever, fixed-fixed, fixed-pinned, and similar configurations. Accelerometers will be attached using adhesives at evenly spaced points across the beams. Two cases will be studied: 1) free vibration characteristics induced by impact forces and 2) forced vibration characteristics induced by an electrodynamic shaker.

Linear modal analysis in addition to the proposed nonlinear analysis will be applied to both the "monolithic" systems and the systems comprised of mechanical joints. This will allow me to verify that the nonlinear analysis is able to reproduce both the linear and nonlinear effects as well as e the deficiencies of the linear modal analysis. EMD will be applied to the measured time series to decompose them into nearly orthogonal IMFs. The extracted IMFs will be used to develop IMOs that capture the local dynamics. The global dynamics will be characterized by superimposing the Hamiltonian FEP with the WT of the measured time series in the energy-frequency domain. A FE model consisting of two linear beams connected by a nonlinear element will be used to compute the Hamiltonian FEP and will serve as the basis for the model updating.

By characterizing both the local and global dynamics, I will be able to develop a reduced order model of the nonlinearity for each particular configuration. These reduced order models will be used to reproduce the dynamics of the measured systems and predict the dynamics of unmeasured systems. Finally, the models will be incorporated into standard FE methods for use in a broad range of applications.

Anticipated Results: 1) The application of the proposed nonlinear analysis methodology will fully capture the linear and nonlinear effects of mechanical joints on the structural dynamics. 2) Reduced order modeling techniques will be developed that can be incorporated into standard FE methods that account for the nonlinear modal interactions produced by mechanical joints.

Broader Impacts: This research aims to apply recently developed techniques to characterize the nonlinear effects of mechanical joints and to incorporate these effects into standard FE models. These models will made available for use in a broad range of applications in fields such as aerospace, automotive, heavy industrial equipment, turbo machinery and structural engineering. As this research progresses, I will present my findings at technical conferences such as the International Modal Analysis Conference and in technical journals such as the Journal of Sound and Vibration and Mechanical Systems and Signal Processing. Furthermore, this research will lay the foundations for developing further methods aimed at understanding nonlinear effects and incorporating them into standard FE analysis methods.

Literature Cited

1. R. Ibrahim, C. Pettit, Uncertainties and dynamic problems of bolted joints and other fasteners, *Journal of Sound and Vibration* 279 (2005) 857-936.
2. N.E. Huang, Z. Shen, S.R. Long, M.C. Wu, H.H. Shih, Q. Zheng, N.C. Yen, C.C. Tung, H.H. Liu, The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis, *Proceedings of the Royal Society A* 454 (1998) 903-995.
3. Y.S. Lee, A.F. Vakakis, D.M. McFarland, L.A. Bergman, A global-local approach to nonlinear system identification: a review, *Structural Control and Health Monitoring* 17 (2010) 742-760.
4. A. Vakakis, L.A. Bergman, D.M. McFarland, Y.S. Lee, M. Kurt, Current efforts towards a non-linear system identification methodology of board applicability, *Journal of Mechanical Engineering Science* 225 (2011) 2497-2515.
5. Y.S. Lee, S. Tsakirtzis, A.F. Vakakis, L.A. Bergman, D.M. McFarland, Physics-based foundation for empirical mode decomposition, *AIAA Journal* 47 (2009) 2938-2963.
6. Y.S. Lee, S. Tsakirtzis, A.F. Vakakis, L.A. Bergman, D.M. McFarland, A time-domain nonlinear system identification method based on multiscale dynamic partitions, *Meccanica* 46 (2010) 625-649.
7. A.F. Vakakis, O. Gendelman, L.A. Bergman, D.M. McFarland, G. Kerschen, Y.S. Lee, *Passive Nonlinear Targeted Energy Transfer in Mechanical and Structural Systems,* Springer Verlag, Berlin and New York, 2008.
8. M. Eriten, M. Kurt, G. Luo, D.M. McFarland, L.A. Bergman, A.F. Vakakis, Nonlinear system identification of frictional effects in a beam with a bolted joint connection, *Mechanical Systems and Signal Processing* 39 (2013) 245-264.

My Personal Journey: Born to a mechanical engineer and a biologist in Johannesburg, South Africa and now a naturalized citizen of the United States of America **my personal journey has been unique and diverse.** Growing up in a post-apartheid South Africa provided me with the irreplaceable opportunity to experience many different cultures. In primary school, my language studies included English, Afrikaans and isiZulu opening my mind to the beliefs, ideals and traditions of multiple cultures. This experience directly influenced and progressed **my appreciation and understanding of a multicultural and multiracial globally-engaged world.**

My family's immigration to the United States of America (USA) ripped me from my established comfort zone into a new, unknown environment. But this change coupled with my family's frequent movement throughout the USA shaped and transformed me into the person I am today. The challenges I faced along this journey allowed me to discover **my passion for science and education**, build **my dreams for the future** and develop the **necessary courage to chase my dreams** while applying my core values and beliefs. I dream of a future where my actions result in **a direct and lasting positive impact on society** and where I can **share my passions with the world through my students, my peers and my research.**

Graduate Study: When I began undergraduate career as a Physics and English double major at University of Akron I lacked direction and an understanding of my purpose. By the time I graduated Summa Cum Laude with a Bachelor of Science in Mechanical Engineering I knew exactly where I wanted to go: I want to **dedicate myself to the continual advancement** of myself and society by serving as a professor of mechanical engineering. In addition to my career objective, I have three motives for pursuing graduate education: to acquire a **deeper understanding** of linear and nonlinear dynamics, vibrations and computational modeling; to develop the skills and resources to **conduct independent research;** and to **become an educator** through teaching opportunities.

Winning the George A. Costello Memorial Fellowship, the Thomas J. and Virginia Fisher Dolan Fellowship, and the Henry L. Langhaar Fellowship at the University of Illinois at Urbana-Champaign (UIUC) propelled me into the Linear and Nonlinear Dynamics and Vibrations Laboratory under the leadership of Dr. Alexander Vakakis, Dr. Lawrence Bergman, and Dr. Michael McFarland. My research focuses on **understanding how nonlinearities transform the system dynamics** through the application of nonlinear system identification (NSI) methods, the development of low degree of freedom (DOF) models that capture these effects and the updating of traditional computational models to incorporate these low DOF models. In the realm of NSI, **I have developed a new approach** that automates the application of masking signal in combination with Empirical Mode Decomposition to decompose signals that exhibit strong mode mixing. In collaboration with Dr. Mehmet Kurt, I am also developing a solution to the Round Robin Benchmark problem developed for the 32nd International Modal Analysis Conference (IMAC). In February of 2015, I plan to travel to IMAC XXXIII to present my results alongside Dr. Kurt.

In addition to my research at UIUC, I have attended several seminars aimed at preparing students for careers in academia. These seminars introduced me to the true purpose and responsibilities of being a professor. Not once have I been disheartened by what I have learned in these seminars. In fact, I am only more **excited and passionate about becoming a professor** after my graduate studies. These seminars have enabled me to plan my graduate path such that I will be exceptionally successful when I begin my career as a mechanical engineering professor.

Research Experience: My co-ops with the Ridge Tool Company, the Toyota Technical Center, and the Goodyear Rubber and Tire Company exposed me to industry driven independent research and development. At the Ridge Tool Company I developed valuable data gathering techniques, experimental model development and strategies for effective communication through presentations to the president of the company. My first major project required me to determine the operating and failure conditions of a new hand tool intended to seal plastic tubing connections by crimping a copper ring around the tubing. An accelerated life test was conducted using a Durant controller, a two way actuator and a custom fixture to simulate the necessary loading conditions. The experiment revealed three failure modes: ductile failure of the handles, shearing of the linkage pins, and fracture and ejection of the cam holder. In order to understand these failure modes, I developed a finite element (FE) model using NX Nastran and calculated the operating stresses. The linkage pins were constrained and the loads were applied to the jaws and handles. My model correctly predicted that the handles would fail first as observed in the experiment. Based on my experimental results and numerical calculations, **I proposed a change in the handle design that would reduce the stress by twenty-five percent and the life of the tool without increasing the costs to manufacture.**

While at the Toyota Technical Center I developed a novel and innovative computational method for modeling piston motion, vibration, and noise contributions. I initiated the project by modeling a single cylinder with only translational DOFs. A special force element was used to model contact between the cylinder wall and the piston. When the piston intersected with the cylinder wall a force with an exponential dependence on the amount of interference was applied at the points of intersection. Following the validation of the initial model, I progressed to modeling a six cylinder engine that utilized both translational and rotational DOFs to model the piston motion. I validated my six cylinder model by comparing the measured lateral and angular piston displacements produced by the computational model with the results obtained through dynamometer testing. With this approach I was able to get **my computational results to match within ninety-five percent of the experimental results.** This was the **first** model developed at Toyota that was able to **accurately predict** the piston lateral and angular displacements inside the cylinder and the corresponding impact on the total engine vibration and noise. **My model was later incorporated into a major development tool produced by my department focused for use by engine development engineers at the Toyota World Head Quarters in Japan.**

At the Goodyear Rubber and Tire Company I participated on an international team of eight vibration engineers tasked with experimental evaluation of classical Transfer Path Analysis and Operational Transfer Path Analysis for use in incorporating vehicle characteristics into noise and vibration analysis and tire development programs. This project allowed me to **develop skills in experimental vibrations** to compliment my computational skills and knowledge. In order to evaluate the two methods, the driver's side front and rear wheels were removed off of a Ford F250 truck and four aluminum studs were mounted on the bolts. Four tri-axial accelerometers were placed on the aluminum studs and another four were placed on the steering knuckle of the both the front and rear positions. Four microphones were placed inside the vehicle's cabin: two located in the driver's seat, one in the passenger seat, and one in the rear. The aluminum studs were struck in three perpendicular directions using a large modal impact hammer and the accelerations and sound pressure levels were measured. During this particular testing phase I operated the data acquisition system along with Bruel & Kjaer's Pulse Labshop while another engineer impacted the aluminum studs. The results of this experiment were used to characterize the contributions of the individual forces to the internal noise experienced by the driver. This knowledge coupled with results from tire dynamometer testing and a numerical design of experiments **enabled the team to developed dedicated design solutions that reduced tire noise without negatively impacting the tire's traction or durability.**

For my senior design project **I led a team of twelve senior mechanical engineering students** that participated in the Air Force Research Laboratory Design Challenge. The challenge required us to develop and build a lightweight device strong enough to lift an overturned 55,000 lb military vehicle. The team decided on a mechanical jack that used four 2 in. diameter ball screws powered by drill motors to transform horizontal work into vertical lifting work. As project leader I inquired on the interests of each member and assigned duties accordingly: two members to develop the control system, two members to design the lifting plates, two members to develop the linkage system, three members assigned to FE modeling using Ansys Structural, and two members tasked with purchasing and manufacturing. My own efforts focused on ensuring that the designs and calculations were accurate; compiling each member's progress into a Power Point presentation for weekly meetings; and design and analysis of the gearing system used to connect the motors to the ball screws. Due to the efforts put forth by the team **we were able to successfully design and manufacture the entire device within only eight weeks and were able to compete at the competition held in Tennessee.**

Broader Impacts: In January, 2013 I was selected to serve as a tutor for the College of Engineering at the University of Akron. Tutoring enabled me to develop a unique skill set that is adaptable to the learning styles of many different students. I believe that tutoring provided one of the most rewarding responsibilities: the opportunity to **directly improve a student's education**; to watch them grow and achieve success under your mentoring; and to **serve as a paragon of knowledge by inspiring an appreciation for learning**. I look forward to future tutoring and mentoring opportunities at UIUC and beyond.

During my time on the University of Akron's SAE Supermileage Vehicle team, I was invited to **address future university students from minority backgrounds** at Goodyear's *Picture Yourself as an Engineer Day* on my experience as a college student. I shared important advice on forming study groups, attending office hours and general tips for succeeding in university. Events like these are **critical for increasing diversity in STEM fields** and I plan to attend similar events during my time at UIUC.

As a result of this lecture, I was invited to address members of the **World President's Organization** on the SAE Supermileage team and the SAE Supermileage competition. I informed the attending members that the Supermileage team's purpose is to design and build a vehicle that attains the highest fuel economy and that our efforts would shape the future for fuel efficient vehicles. **I believe that the inclusion of all races, genders and ages is absolutely crucial and essential to advancing society and solving its biggest issues**. I aim to actively involve as many unique and different voices in my future as is possible.

Conclusion: Winning the George A. Costello Memorial Fellowship, the Thomas J. and Virginia Fisher Dolan Fellowship, and Henry L. Langhaar Fellowship at the University of Illinois at Urbana-Champaign propelled my academic career and enabled me to reach where I am today. Winning the NSF Graduate Research Fellowship would enable me pursue my research interests and outreach goals without the constraints and pressure of finding funding. This fellowship would **empower** me to become not only **a world class researcher**, but also a **world class educator and mentor** through a **robust** career as a professor of mechanical engineering.