High-rate Structural Health Monitoring: Part-I Introduction & Data

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ABSTRACT
Engineering systems operating in extreme dynamic and complex environments pose various challenges to designers and researchers. Examples of such systems include active safety systems in transportation (1) space: supersonic vehicles, space launch systems, and space infrastructure, (2) air: unmanned aerial vehicle (UAV), hypersonic vehicles, electric vertical take-off and landing (eVTOL), (3) ground: cars, trucks, and (4) underwater: Unmanned Underwater Vehicles (UUVs). These structures can experience acceleration and difficulties exist with amplitudes higher than 100 g_n for a duration of under 100 ms. The multi-resolution timescale of these challenges requires system designers and control engineers to leverage cutting-edge tools to provide the next generation of reliability and serviceability. Particularly, the recent development of high-rate machine learning (HRML) methods enabling high-rate Structural Health Monitoring (HR-SHM) offers the potential to enable these next-generation active structures. Part I of this III part tutorial will provide attendees with an organized discussion of the challenges related to the topics of interest high-rate dynamics, challenges related to data development, and the unique role unmodeled dynamics play in high-rate systems.

Keywords: structural health monitoring, high-rate dynamics, decision-making, machine learning, data set

INTRODUCTION

Structural Health Monitoring (SHM) is an approach to monitor structures for the current state of health and applies to both static and highly dynamic engineering systems [1]. With the advent of real-time sensing, edge-computing, and high-bandwidth computer memory, there is new capability and focus area emerging: high-rate SHM (HR-SHM) [2]. This extended abstract overviews part I of a III part tutorial on high-rate structural health monitoring. This extended abstract overviews: topics of interest in high-rate dynamics, challenges related to data development, and the unique role unmodeled dynamics play in high-rate systems.

The ultimate goal of SHM and prognostics is to accurately monitor a structure's functional integrity, remaining life, and react to maximize function and minimize risk. The SHM technical community has developed many successful approached for monitoring the health of static structures with low-frequency responses [1,2,3,4]. Structures with high-rate dynamics include civil structures exposed to blast, automotive safety systems subjected to collisions, debris strikes to space shuttles, and aerial vehicles [5,6]. The monitoring systems for high-rate SHM (HR-SHM) have many additional technical challenges to overcome for appropriate monitoring the functional integrity of high-rate dynamics. High-rate dynamics have been previously defined by Hong et.al [7] as:

> "a dynamic response from a high-rate (<100 ms) and high-amplitude (acceleration > 100 g_n) event such as a blast or impact. […] A system subject to high-rate dynamic environments can often experience sudden plastic

deformation, and damage can extend to the structure, electronics, and/or sensors […]. The high-rate problem contains many complexities that can be summarized as having:

1. large uncertainties in the external loads;
2. high levels of non-stationarities [in the structure] and heavy disturbances;
3. unmodeled dynamics from changes in system configuration."

The complexities of high-rate dynamics drive the need for a specific technical area of HR-SHM and prognostics. To further define the timescales of the problem, the community has recently defined the timescale nomenclature as [2]:
" timescale regimes are for the time elapsed between event detection to decision-making (i.e. latency), these regimes are:

1. High-Rate – 1 ms
2. Very High-Rate – 100 μs
3. Ultra High-Rate – 1 μs"

The first goal for the technical community is to develop HR-SHM methods that target 1 ms timescales from event detection to decision-making. With this, the attribute for high-rate dynamic and timescales for HR-SHM have been defined and will be used and referenced during the tutorial.

HIGH RATE AND UNMODELED DYNAMICS

Two Key attributes associated with the high-rate dynamics that make estimation and detection methods challenging include: (1) lack of physical knowledge and (2) inconsistency of high-rate events [2].

The lack of physical knowledge of the high-rate process and presence of unmodeled dynamics and loading events prevents simplifying assumptions and therefore preventing simple methods for monitoring and evaluating the system dynamics. This lack of information drives a need for a combination of system identification, load estimation, and damage detection (all forms of complex inverse processes). Additionally, the poor observability in the sensing procedure, the poor quality of data, and challenge of adequate high sampling rate make it difficult to make up for the lack of physics with only data-driven modeling. The lack of physical knowledge greatly increases the challenge to obtain structural awareness of the with high-rate dynamics through learning the state of a structure online during a high-rate dynamic event.

The lack of consistency and/or repeatability of high-rate events combined with unmodeled dynamics dives nonstationary responses in structures. While the physics is not clear for many high-rate processes, the consistency of high-rate testing/events are normally very low. During high-rate events, a structure will often generate previously unmodeled dynamics due to changes in system configuration or damage. The presence of unmodeled dynamics challenges the ability of methods to obtain environment awareness. The lack of awareness of boundary conditions and loading events brings very high uncertainties and a tremendous amount of difficulties in predictive modeling, such as damage prognostics.

DATA SET DEVELOPMENT

A critical need for the development of HR-SHM is experimental validation for the high-rate algorithms [2]. To enable a tractable comparable analysis of different algorithms for HR-SHM, data sets from various experimental tests that have different aspects of the high-rate dynamics would be collected and distributed for development of new approaches and testing algorithms. These data sets should be sufficient to cover the considered time scales (and have multiple "goals" that the data owners want to get out of the exercise), should sufficiently span a large range of operational and environmental variability, and should have numerous instances of whatever "failure" mode targets are desired (e.g., structural damage, the operability of electronics, actuators, etc.). To have sufficient data for the development and validation of HR-SHM the experimental testbeds should be able to be run in repeatable and controllable high-rate dynamics to have bounded experimental variance of the complex system responses. Coupled with the data would be the need for appropriate metrics, design of experiments scenarios, and different situations. To date, the technical community is limited in the development of the key experiments and datasets needed to support the HR-SHM development.

The Air Force Research Laboratory Munitions Directorate has designed a testbed to generate reproducible datasets for the area of high-rate structural health monitoring (HR-SHM). The testbed is named Dynamic Reproduction of Projectiles in Ballistic Environments for Advanced Research, or DROPBEAR, and was introduced in [9]. A large DROPBEAR dataset was recently documented and presented to the community for distribution and use [10]. The testbed consists of a cantilevered beam with two controllable and repeatable state changes: an electromagnetic mass attached at its tip to reproduce a step change in mass and an attached rolling cart to reproduce time-varying changes in boundary conditions. DROPBEAR is not a true high-rate system as defined by the HR-SHM community [2] due its low frequency response and not intrinsically high-rate by the above definition. Although strictly a high-rate system, the DROPBEAR provides the research community with data to evaluate the balance of short time scales and changing dynamics constraint posed by the HR-SHM problem, with the challenge to estimate, detect, and predict changes in structural states.

CONCLUSION

This is a brief introduction to High-rate Structural Health Monitoring as part I of a three part tutorial. The HR-SHM technical area has unique challenges that need to be addressed due to presence of high-rate dynamics, challenges associated with the replication of high-rate dynamics in controllable ways for training data, and how unmodeled dynamics affect in high-rate systems and the implications for monitoring the complex system.

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