Sensor Network Design Technique for Monitoring Railroad Structures

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ABSTRACT

Components of high speed trains such as bolsters and bogie are subjected to continuous dynamic loads under varying environmental and operational conditions. Scheduled maintenance of these components at regular intervals is not feasible as these inspections are costly, burdensome, and increase structural downtime. Moreover these conventional inspections require dis-assembly of different components of the train structure. Oftentimes these dis-assemble and re-assemble operations leads to new damage initiation if these operations are not followed correctly. Structural Heath Monitoring (SHM) technologies are ideal solutions to monitor this kind of critical structure.

Guided Wave-based Structural Health Monitoring (SHM) techniques are currently widely used in aerospace and energy industries to monitor structural damages such as fatigue crack, delamination, debond, and corrosion etc. The damage detection sensitivity of any SHM technique highly depends on the sensor network design. This paper presents model-based quantification technique to design and verify the performance of the sensor network. In a joint program between the CRRC and Acellent Technologies, sensor network design techniques were demonstrated and validated through case studies on high speed train bolsters.

INTRODUCTION

Over the last two decades several innovative developments have allowed trains to move at high-speed. Components of high speed trains such as bolster, bogie, car body etc., are subjected to continuous dynamic loads under varying environmental and operational conditions for long duration. Many components of high speed trains are junctures with welding interfaces which are considered to be crucial areas under highly varying dynamic stresses. The consequence of high stress loading results in an initiation of fatigue cracking [1] that becomes a major concern to the field operators in order to maintain the safety of a high speed train system.

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Structural Health Monitoring (SHM) is an emerging technology in the aerospace, civil, and pipeline that is being utilized for structural integrity monitoring and asset management. SHM technology is perceived as a revolutionary approach to enhance structural inspection and management providing the ability to move away from costly and time-consuming manual inspection toward cheaper and faster automated structural monitoring. By leveraging modern low-cost sensors and data acquisition designs and combining this with powerful signal processing algorithms, SHM aims to detect and track damage over time allowing for timely, targeted and cost-effective maintenance of the monitored structures. The use of permanently mounted sensors in SHM systems provides a more effective technique over traditional non-destructive evaluation approaches in that the sensors can be easily installed on those areas, difficult to inspect without extensive structural disassembly.

Designing sensors is a critical process in the development and deployment of a SHM system. In order to meet the requirement of detectability, serviceability, and durability for a SHM system to perform functions over a period of the structural life cycle, the sensor system must have:

- Robust integration with the structure. The sensor is applied with suitable bonding agent materials, adhesives, protection materials for long-term durability and operation.
- High accuracy in detection performance. The number of sensors required for use in detecting and localizing damage is determined based on the sensor design for detectability. Sensor layout may have different distribution density based on the structural configuration and critical monitoring areas. In the sensor design process, the scenario of sensor layout is verified with a simulation tool to insure the result from the design meets the goal of detectability.
- Sensor reliability for long-term operation. The sensors used have proven long-term reliability in the aerospace industry and conforms to military standards.

**SHM TECHNOLOGIES IN DEMAND AND PROPOSED SOLUTIONS**

There are currently many sensors in a high speed train system to monitor key components and their performances as shown in Figure 1, such as, electronic sensors for voltage and current, temperature sensors, air pressure sensors, accelerometer sensors, gyro sensors, chemical detection sensors and fire alarming system etc. SHM systems can expand these sensing capabilities with dynamic strain monitoring, corrosion detection, fatigue crack detection, impact detection sensors etc.
In collaboration with Acellent technologies, CRRC is currently testing a SHM system framework for a high speed train. The system utilizes Acellent’s SHM-Patch Hot Spot Monitoring system (SPHSM). The system is comprised of Acellent’s patented SMART Layer® technology, “on board” ScanGenie data acquisition hardware, and SHM Pro-SHM Patch analysis software system as a complete solution for use in high speed train. The system can be used to monitor multiple hot spots on structures such as bolsters through the use of distributed sensor networks.

INNOVATIVE MODELLING TECHNIQUES

Innovative modeling techniques utilizing the concept of computerized companion technologies for design, analyze and validation of the performance of the physical asset, such as a structure, have been developed for the high-speed train. These techniques are currently widely used for designing the SHM sensor network. The Computer Aided Design (CAD) process is the main routine in the creation of the model from a physical structural. The CAD model can be used for designing the sensors, connectors, mounting mechanism and performing multi-physics analyses such as in the areas of dynamic stress, vibration, and thermal studies based on the designed configuration.

SENSOR NETWORK DESIGN PRINCIPLE

Acellent has developed the SHM Patch Hot Spot Monitoring system (SPHSM) which was widely used in the aerospace industry for monitoring fatigue crack and corrosion damages on the structures. In the application of high-speed railroad system, each structure has its uniqueness and special requirements in order to meet the requirements for the application. Figure 2 illustrates the design processing flowchart that can be standardized and applied to the high speed train system:
- Create and use a CAD model for assistance of sensor design
- The model is run through the Finite Element Analysis model with design criterion for identification of the structural issues at each hot spot
- Results from the Finite Element Analysis are input to the sensor design process for determination of number of sensors and location of sensors strategies with defined obstacles, keep-out zones, high stress/strain zones
- The sensor design is created using a three-dimensional (3D) software environment along with with the sensor model
- Finally, the 3D sensor design result is input for design in the final manufacturing process. The design is manufactured to obtain the final sensor network layers.

Figure 2. Sensor Design for a Bolster Structure of a High Speed Train.

When designing SMART Layer sensors for a structure, the following procedures are required:

1. Step 1: Select critical zones in the structure for monitoring
2. Step 2: Identify the damage type and sizes
3. Step 3: Determine the actuation and sensor spacing to form an effective sensor network
4. Step 4: Determine the sensor network sensitivity to the damage by verifying the probability of detection with the sensor network, i.e., $POD_{network}$.

**Detection Requirement and Critical Damage Size**

Detection Requirement is usually referred to the detection goal of a SHM system in its normal operation environment. To quantify the detection requirement, the context of critical damage size is used as for minimal detectable damage size. The minimum damage size is usually provided by the inspection process where a plan to repair/replace the structure exists in order to mitigate the risk of structural failure.
Sensitivity Analysis for Determining the Number of Sensors

Sensitivity analysis is a critical process prior to the determination of how many sensors are to be used and where to place them. In SHM monitoring, there is a systematic method to determine the sensitivity to damage based on a wave propagation model that uses a probability of detection technique. Wave propagation parameters at different frequencies are measured through testing. Knowing wave velocity and actuation frequencies, wave lengths can be estimated. Knowing the minimum detectable damage size and wave lengths at different frequencies, actuation wave frequencies can be selected. Typically, at lower wave length (higher frequencies), sensor signals are more sensitive to smaller cracks but at higher frequencies, wave attenuation is very high which limits the wave propagation distance. A sensor design verification tool is able to validate whether the current sensor design is satisfied with the minimal detectable damage size.

Optimization Process of Sensor Network Design

The design process can be run iteratively in order to achieve the optimal sensor network design. Acellent’s Sensor Design Verification Tool was developed based on the Lamb wave sensor network probability of detection ($POD_{network}$) theory. The $POD_{network}$ model based verification tool uses a Genetic Algorithm (GA) based optimization approach. Figure 3 illustrates the general concept of how the $POD_{network}$ model based optimization tool is used for the optimization of sensor design.

![Figure 3. Sensor Design Optimization Process using $POD_{network}$ Tool.](image-url)
SENSOR RELIABILITY

SHM Sensors are designed to operate reliability for the designed life of the structure. In general practice, sensors may be designed with a specialized protection mechanism such as coating, mechanical packaging, and other protection materials.

The sensors are designed to operate in the high-speed rail environment including vibration, temperature, moisture, blowing sand etc.

CONCLUDING REMARKS

Online structural health monitoring technologies are gaining interest by high speed railroad and train operators due to the ease of monitoring ability on several critical components. Testing is underway to evaluate and deploy the SHM system in the areas of bolsters, bogies, and car bodies. The goal of the SHM deployment is to monitor structural health and ensure the safety of the structures while reducing inspection costs. The applications of SHM system for a high speed train system require additional testing and validation before the systems can be approved for deployment. The systems can enhance the effectiveness of asset diagnostic management and provide critical inputs for technologies of prognostics and prediction of the remaining life for railroad systems.

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REFERENCES


