Structural Health Monitoring System for Big Thunder Mountain Railroad Roller Coaster

SE 163: Structural Health Monitoring
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Operational Evaluation 10/10
Data Acquisition 10/10
Feature Extraction 10/10
Statistical Modeling 6/10
Data Normalization 10/10
Issues and Challenges 10/10
Technical Grade 56/60
Grammar Grade 54/60

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Introduction

September 5, 2003 the Big Thunder Mountain roller coaster at Disneyland in Anaheim, California derailed killing one person and injuring 10 others. The report filed by the California Department of Occupational Safety and Health (DOSH) found that loose restraining bolts, which secure an upstop wheel on the engine of the train, caused the accident. [1]. The upstop wheel ran on the underside of the track and secured the locomotive to the track during high accelerations. The upstop wheel itself was connected to a floating axle running beneath the track as shown in figure 1. After approximately 12 runs through the track, the loose restraining bolts worked themselves completely out causing the upstop wheel to fall away from the engine 1/3 of the way through the ride. The loss of the upstop wheel caused the floating axle to drop to the track level where it collided with the rails of the track. Upon reaching an uphill portion of the track while traveling through a tunnel, the loose floating axle damaged a position sensor on the track sending an emergency stop signal to the operators and prohibiting the release of any other trains onto the track. The floating axle then wedged between a section of the track-mounted emergency braking system and the engine causing the back portion of the engine to lift up (graphic showing this would be helpful). The towbar connecting the engine to the first cart (cart 1), which contained passengers, snapped causing cart 1 to slam into the underside of the engine. This impact was determined to be the direct cause of death for the passenger sitting on the right side of the front row in cart 1. In addition, this collision caused the engine to become jammed between the top of the tunnel and the track. After coming to a stop, the carts began to slide downhill separate from the engine and triggered a second position sensor. This sensor sent an emergency stop signal throughout the braking system immediately stopping all trains including the carts involved in the accident.

![Figure 1: Upstop Wheel and Floating Axel on Big Thunder Mountain Engine](image)

The report issued by DOSH concluded the train design was safe and that human error lead to the two main causes resulting in the failure: the restraining bolts had not been properly tightened, and a safety wire (what does this do?) connecting the upstop wheel to the engine had not been attached. While Disney had procedures in place to prevent such a
tragedy, the procedures were not properly followed or understood by the mechanics working on the trains [1].

To eliminate the possibility of future accidents a structural health monitoring (SHM) system developed to monitor the condition of the wheel brackets and restraining bolts should be implemented. By designing the system to be a permanent fixture, the potential for human error can be reduced. *(I’m not sure this will reduce human error, rather it can mitigate consequences of human error)* In addition, such a SHM system could move the maintenance schedule from a time-based system to a conditional-based system (currently the trains are checked every 72 hours for damage) resulting in significant cost savings.

**Operational Evaluation**

The SHM system design will focus along the undercarriage of the roller coaster in the interests of preventing loose connecting bolts, localizing the SHM system to reduce cost, and to reduce the data load. Before any structural health monitoring system can be reliably designed, a careful evaluation of the structure, its means of operation, and its environmental surroundings is necessary. This evaluation helps determine the requirements the SHM system must meet in order to prove effective as well as identify limitations that will be placed on the SHM system. In particular, the definition of damage, the economic and life-safety justification, the environmental and operational variability, and the data acquisition limitations are discussed below.

**Definition of Damage**

The types of damage a SHM system for the Big Thunder Mountain roller coaster should be able to detect include: (1) loose and/or missing bolts, (2) floating axel and wheel corrosion, and (3) cracks. Due to the lack of geometric specifications, material properties, and manufacture recommended specifications, precise values for critical corrosion damage, critical crack lengths, and minimal torque requirements for the bolts are not determined in this paper. Once the decision to install the SHM system on the roller coaster is official, more attention will be needed to define these critical conditions using material property calculations.

For the purpose of developing the initial design for the SHM system it will be assumed that cracks (new and/or existing) above 0.5 cm in length have the potential to result in failure. This assumption is based on a critical crack calculation performed using the material properties of steel [2].

\[
a_c = \frac{1}{\pi} \left( \frac{K_{IC}}{\sigma} \right)^{\frac{1}{2}}
\]

(Eq. 1)

In this equation \( a_c \) is the critical crack length and the following properties were assumed: fracture toughness \( (K_{IC}) \) of 50 MPa*m^1/2, yield strength of 300 MPa, and a critical stress \( (\sigma) \) equal to the yield stress (assuming it would never be anywhere near that high). \( Y \) is a constant related to the crack geometry and was assumed to be 1. The resulting estimated crack length is 1 cm. After including a factor of safety of 2, the minimum crack length that should be detectable becomes 0.5 cm. It is important to note, however, that
this calculation requires a steel thickness of 7 cm, which is most likely thicker than any of the structural parts on the train.

Quantification of the maximum acceptable amount of corrosion can be determined by predating the fatigue life of the structural members given a reduction in the mass, physical dimensions, and surface quality of the structural members caused by corrosion. Again, assuming a steel structure, a reasonable limit on the amount of allowable corrosion would be one that reduces the fatigue limit of the structures below the stresses experienced during normal operation. A reduction of the fatigue limit below these normal stresses results in an increased potential for crack propagation and brittle failure.

For the bolt torque specifications, the minimum allowable torque for each bolt could be set at the limit where the boundary conditions for the connected parts begin to change under the typical loads experienced during normal operation.

**Economic and/or life-safety justification to perform a NDE**

Big Thunder Mountain roller coaster was designed and manufactured by Walt Disney Imagineering and has been in operation since 1979. The number of roller coasters that use the same design methodology of a floating axle is not known at this time, but the use of upstop wheels is prevalent among roller coasters around the world.

Currently Disney performs preventative maintained on a time-based schedule. Maintenance is performed on passenger-carrying devices every 72 hours, regardless of the train’s condition [1]. If a feasible SHM system were introduced to monitor damage, Disney could have an economic benefit from the possibly of transitioning from time-based maintenance to condition based maintenance, saving in the amount of labor hours and parts used. While the money saved from the reduced labor hours can be significant, an even larger savings can be expected by reducing the number of accidents occurring on the Big Thunder Mountain roller coaster. It is important to note that 24 passengers on this roller coaster have been injured since 2001 alone (need reference when quoting statistics like this). Aside from reducing the number of injuries, an effective SHM system can greatly reduce the associated costs of litigation suffered by Disney. The use of emergency procedures for train operators is also an important consideration for justification. A SHM system could, using colored diodes for example, signal to operators that damage (and to what degree) has been traced, or automatically communicate with the roller coasters control system allowing it to stop the trains. Therefore, the most poignant justification for a SHM system would be: 1.) The life-saving benefits associated with operators being more cognitive and able to act in the event of adverse conditions and 2.) The economic benefits of minimizing maintenance staff, replacement parts and potential law suites by mitigating injured patrons. Also, provides more continuous monitoring

**Environmental and operational variability**

Variability in the conditions of the Big Thunder Mountain roller coaster and its surroundings are considered through two general categories: environmental and operational quantities.
The track and trains of the Big Thunder Mountain roller coaster are exposed to the elements allowing the weather to play a role in the conditions the trains are experiencing. The climate of Disneyland California is Mediterranean [3]. The average summer temperature is 72 degrees Fahrenheit and the average winter temperature is 53 degrees Fahrenheit. Low humidity, an annual rainfall of 14 inches, and 328 days of sunshine a year add to the mild climate conditions of Disney. Another variability is the occurrence of earthquakes. They are considered a major threat to the city of Anaheim resulting from the proximity of several fault zones, notably including the San Andreas Fault Zone and the Newport-Inglewood Fault Zone [4]. However, the probability of an earthquake/s with magnitude 7 or higher has less than a 10% chance of occurring for the next 20 years. Lastly, the roller coaster runs along a “dry” track, i.e. it does not pass through areas in which the track is submerged in bodies of water. While environmental variability will be a definite concern when designing the SHM system, it would seem appropriate to deduce that with the mild climate of Anaheim coupled the low probably for occurrence of hazardous earthquakes, the variability caused by the environmental conditions will be less significant then the variability introduced by operational variability.

The wide range of conditions the Big Thunder Mountain roller coaster may be operated in results in significant variability in the measurements a SHM system might make. For example, on a busy day the roller coaster might be running with as many trains as possible filled to their maximum capacity circling the track, while on a slow day just one or two trains might be running, each at less then half capacity. Changes in the load, both in terms of number of people on each train and number of trains on the track, will affect the vibrational qualities of the upstop wheel brackets as well as the track itself. In addition, the passenger load of each train can cause the kinematic quantities, such as top speed and acceleration around each turn to vary, which can add undesirable offsets to any measurements of these quantities. Along with the effects of loading, several other parameters such as the condition of the bearings in the roller coaster wheels and the level of vibration introduced by external sources (such as nearby construction or traffic) will need to be accounted for by the SHM system.

**Limitations on acquiring data**

Limitations on data acquisition can be narrowed to two areas: wired vs. wireless system, and system placement. Wired systems cannot provide real-time data when the train is en-route. Once in the station, the wired system can be docked (via operator or machine) to a data acquisition system and provide analysis on the train’s condition. If the train is checked during each run, the amount of delay caused by docking could significantly increase the time patrons wait in line. To reduce ride wait time, data would most likely be downloaded from the train once or twice a day. A wireless system poses more convenience for continuous monitoring because it can provide real-time feedback. If the train experiences a critical failure during a run, an emergency signal could be transmitted to the brake system, stopping the train from continued use. In an effort to increase the SHM systems battery life, a low-powered system could be used that allows wireless communication over very short distances and at infrequent intervals (such as once per trip around the track). If this (what?) proved to provide insufficient monitoring, the system
could be modified such that it would be capable of emitting a powerful emergency signal in the event of a catastrophic failure. If powerful enough, this signal could notify the roller coaster’s operators of the emergency condition regardless of the train’s location on the track. An additional limitation of a wireless system is the fact that transmissions can go “missing”. To eliminate the potential for catastrophe caused by an unreceived signal, it will be important that the station be able to communicate with the wireless system if a signal appears to be missing. While both wired and wireless systems could provide information on the structural conditions of the trains, a SHM system with wireless capabilities should be used because it will have fewer limitations and be more appropriate to monitor the needs of the roller coaster.

The SHM system placement is limited to static features of the trains dynamic system. This poses some possible obstacles for wired systems. If a system spans the length of the train, wires jumping from car to car will need a certain level of slack. Enough to allow full range of motion on the car, but not so much that wire could extraneously hang too low and get caught and pulled loose. Also, the system’s battery pack/s must be small enough, yet powerful enough, to fit in discrete locations in the train so it can be secured during the train’s normal operations. Because the sensors that most likely will be used (accelerometers and piezoelectric patches) are small, sensor placement should not be a problem. It should be easy enough to place the sensors near to both the bolts attaching the upstop wheel as well as near possible stress concentration points where fatigue cracks might start. However, the flexibility of the sensors might be a concern in that sensors might need to be applied to non-planar surfaces to be optimally situated.

**Hardware System**

The wireless SHM system for the Big Thunder Mountain roller coaster will most likely consist of strain or acceleration sensors, a computational core, a wireless transmitter, batteries, and a station mounted computer.

**Sensors**

The primary requirements for the sensors to be used on the Big Thunder Mountain roller coaster, are they must be small enough to fit on relatively small parts, and they must be able to withstand the high g-forces experienced by the roller coaster while still providing adequate resolution of the low amplitude vibrations that will be used to detect damage. To monitor the tension in the bolts holding the upstop wheel to the cart, at least one sensor, and more likely two sensors, will be needed at each wheel. Both piezoelectric, Lead Zirconate Titanate (PZT), based strain sensors and accelerometers, as well as MEMS based accelerometers may be used in the Big Thunder Mountain SHM system. PZT sensors have the advantage that they can be used not only to measure vibrations, but through the application of an electric field they can cause vibrations in the structure of interest [5]. Taking advantage of this property of PZTs, sensors an active sensing system can be set up where the vibrations produced by an “actuator” PZT can be sensed by the surrounding “sensor” PZTs providing an indication of damage between the actuator and
sensors. Some basic information on PZT [5] and MEMS [6] bases sensors is given below:

PZT (Lead Zirconate Titanate) Sensors:
Size and Shape: PZTs can be trimmed to size and bought as disks up to ~5.0 cm. diameter, or sheets up to ~5.0 x 3.0 cm.
Sensing Range (elongation): ~1 to 100 µm
Voltage Supply (in actuator mode): 40 to 60 V
Voltage Supply (in sensing mode): 0V
Current Supply (in actuator mode): ~ 1 mA
Cost: $10 to $30 each (in bulk)

MEMS Sensors:
Size: ~5 mm x 5 mm x 2 mm
Sensing Range (acceleration): ± 1.7 to ±10.0 g
Voltage Supply: 4 to 6 V
Current Supply: 0.6 to 0.7 mA
Cost: $3 to $9 each

Computational Core
To read the data, perform some initial calculations, and to transfer data to the wireless unit 6 computational cores will be needed for each train (one per car and one in the engine). To interpret the signals coming from the accelerometers, analog to digital converters (ADC) will be necessary. To prevent aliasing, the ADCs should be able to sample at a rate at least twice as fast as the highest frequency of interest, and ideally it should be able to sample at ten times the highest frequency. In addition either a digital or analog low pass filter should be provided to prevent folding effects in the higher frequencies. Because each cart will have a computational core along with the high cost of ADCs, it will be most practical to have just one ADC per computational core and including a switching mechanism that allows 8 or more channels to sequentially pass through the ADC (2 accelerometers per wheel * 4 wheels per car).

The drawback of such a system however is the phase information can become distorted by the switching process. Realizing that it requires much less power to run computations then to transmit data, it is desired to reduce the data as much as possible without loosing any possible damage detection features before transferring it to the roller coaster’s control system. In a bridge study by Lynch, et al. [7] a two processor computational core was used as part of a wireless SHM system. An 8-bit Atmel AT90S8515 microcontroller was used to operate the data collection unit, and a 32-bit Motorola MPC555 PowerPC microcontroller was used for data analysis. By using a combination of the two processors, a compromise was reached between computing power and electrical power requirements. Lynch also included 448 Kbytes of flash ROM and 26 Kbytes of RAM for data storage.
Because Lynch only recorded one channel worth of data with each computational core, the computation cores for the Big Thunder Mountain will require approximately 8 times the memory, and possibly a substantial increase in computation power to be able to record and analyze 8 channels worth of data.

**Wireless Transmitter**
To keep the cost down one wireless transmitter will be used to transmit the data collected and processed by all 6 computational units per train. In order to get the data from the computational units to the wireless transmitter a flexible wiring harnesses will be needed to protect the wires running from cart to cart. If the data is only to be transmitted when the train is in the station, a range of 50 – 100 m should be sufficient. On the other hand, if the data is to be transmitted continuously throughout the ride, either a range of 2-3 km would be necessary, or receivers would need to be placed all along the track and connected via wires to the station. A compromise between power savings and the ability to monitor the safety of the roller coaster can be reached by developing a system that usually only transmits data when the train is in the station, but is capable of drawing more power from the battery allowing it to transmit from any part on the track. By including an algorithm in the system software to detect catastrophic failures (such as a wheel falling off), the system can be programmed to send a short, high powered, emergency signal to the roller coaster’s control system, causing the system to stop all trains on the track. Honeywell Sensotec [8] currently makes a Model 2116S wireless transmitter and a Model 2145A receiver that could possibly be modified for use in the Big Thunder Mountain SHM system. The transmitter has a bandwidth of 2000 Hz and draws 350 mW.

What about employing a “hopping” approach where each unit send information to unit on locomotive and this unit then transmits data using more powerful transmitter that is tied to power on locomotive, if in fact the locomotive has power.

**Batteries**
To ensure the continuous operation of the SHM system a separate battery should be included with each computational unit and with the wireless transmitter. If each battery is large enough to power its intended component for 2 days, yet is recharged every night, the risk of losing battery power should be minimized. In addition the system should be wired in such a way that if one battery fails, the additional batteries on the train should be able to carry the load the failed battery was intended to carry. For ease of use, a single plug on the outside of the train should be used to provide recharging power for all the batteries. Because the batteries are to be charged without first being completely discharged, NiMH or lithium-ion batteries will be the best option because they do not exhibit the “memory effect” define terms like this or use reference many other batteries have.

**Station Mounted PC**
Depending on the ability to utilize the roller coaster's current computer and control system an independent personal computer may be necessary to provide the means to evaluate the data and display any safety warnings. The software on the computer needs to be able to:

- Detect signs of damage
- Warn the ride operators immediately so they can remove the cart from the ride
- Communicate with the roller coasters control system in the case of catastrophic damage
- Store the information so mechanics know where to start looking when they make their repairs.

A standard personal computer running Windows or Linux based operating systems should provide more than enough computational power and memory to run the damage detection software.

**Damage Detection Features**

There are several possible means to “watch for damage” each with several damage detection features that could be used to quantify the existence of damage. Two methods considered for the Big Thunder Mountain roller coaster because of their ability to locate damage are the impedance-based method, and the Lamb-wave-based method.

**Impedance-Based Damage Detection**

As discussed by Park, et al. [9] Impedance based damage detection techniques provide rapid damage detection with minimal computations. This damage detection method is based on the measured electrical impedance of a single PZT patch connected to the structure of interest. Because piezoelectric materials produce an electrical charge when stressed, and produce a strain when subjected to an electrical field, the measured impedance of the PZT patch is a coupling of the electrical impedance of the PZT and the mechanical impedance of the structure. Assuming the PZT patch does not undergo any changes, a change in the measured impedance of the coupled PZT/structure system compared to a prerecorded baseline would indicate a change in the structural stiffness or damping which could indicate damage. Typical impedance-based SHM systems use a sinusoidal input to the PZT, which ranges in frequency between 30 and 250 kHz. Higher frequency inputs are capable of detecting smaller scale damage as a result of their decreased wavelength.

To quantify any system damage, Park, et al. used a damage metric defined as:

\[ M = \sum_{i=1}^{n} [\text{Re}(Y_{i,b}) - \text{Re}(Y_{i,t})]^2 \]  

(Eq. 2)

where \( Y_i \) represents the electrical impedance of the PZT at frequency interval \( i \). The subscripts \( b \) and \( t \) stand for the baseline and test cases. The damage metric \( (M) \) is a single value giving the sum of the square of the differences between the baseline and potentially damaged cases. The larger the damage metric the greater the structural changes between the baseline and a test case.

**Lamb-Wave-Based Damage Detection**

Lamb wave based SHM systems require two or more PZT patches in order to detect damage in plate-like structures. One PZT patch will act as an actuator providing a waveform that will travel through the structure away from the PZT. The other PZT patches will act as sensors and will detect the waveform produced by the actuator. By routinely stepping through the PZT patches, such that each patch will be an actuator
while the surrounding patches are sensors, a complete “picture” of the structure can be developed. Yang, et al. [10] developed a SHM system for space vehicles thermal protection systems that detects damage by comparing the amplitudes of the measured Lamb waves to baseline measurements made before damage was implemented. Depending on the geometry and structural properties of the structure as well as the power input to the actuating PZT patch, Lamb waves can travel long distances and thus cover a large area.

Two methods of damage quantification for Lamb wave techniques are considered for the Big Thunder Mountain roller coaster. The first is a time of flight comparison. By measuring the time it takes the waveform input to the structure by an actuating PZT to reach a sensing PZT for both the baseline and potentially damaged cases, conclusions can be made on how the structural properties of the material between the two PZTs has changed since the baseline measurement was made [10].

The second damage quantification technique is to compare the kinetic energy of the waveform received by the sensor PZT in both the potentially damaged and baseline cases. Sohn et al [11] used a damage index (DI) given by:

$$DI = 1 - \frac{\int_{u_0}^{u_1} W_f(u, s_0)^2 \, du}{\int_{u_0}^{u_1} W_b(u, s_0)^2 \, du} \quad \text{(Eq. 3)}$$

where $W_f(u, s_0)$ is the wavelet transform of the portion of the signal representing the waveform of interest. The subscript $t$ represents the test case while the subscript $b$ represents the baseline signal as in the impedance-based method. To minimize the amount of data recorded, and to concentrate on the frequency of interest, the wavelet transform is only taken at one scale value ($s_0$) representing the center frequency of the input waveform supplied by the actuating PZT. The translation ($u$) is proportional to time with the range ($u_0$-$u_1$) representing the portion of time where the waveform of interest is measured by the sensor PZT. Realizing that as the waveform passes through a region of damage a portion of the waveform’s energy will be reflected, the total energy that reaches the sensor PZT will be less then the energy that will reach the PZT in an undamaged case. From equation 3 it can then be seen that the DI will always be between 0 and 1 with values close to 0 representing little to no damage and values close to 1 representing significant damage.

**Emergency Stop System**

In addition to either a Lamb-wave or impedance-based damage detection system a simple emergency system can be set up to send out the emergency stop signal when a wheel actually falls off. By setting up a simple low powered electrical circuit through the upstop wheel brackets and the frame they are attached to, the SHM computational core can be programmed to send the emergency stop signal to the roller coasters control system whenever the circuit is broken. Before this system is implemented however, it will be crucial to ensure that the possibility of false-positive readings is minimized. Emergency stops of the roller coaster when it is in working condition could prove to be detrimental to the roller coaster’s image, as passengers might believe the system to be damaged and unreliable.
**Implementation**

A visible wheel on the topside of the track, and the upstop wheel underneath secure the Big Thunder Train engine and cars to the track. These two wheels pinch the track, preventing the train from lifting off the track. The floating axle, connecting the two wheels, can pivot, allowing the car to swing around curves and bends in the track. To best detect damage implementation of an Impedance-based and Lamb-Wave-based measuring system should be positioned in the locations most likely to experience changes caused by damage.

**Impedance-Based Damage Detection**

Because the impedance-based technique has a relatively small range compared to the Lamb-wave technique, one PZT sensor should be placed as close to each wheel bolt as possible. Placement of the sensors could be accomplished during a selected scheduled maintenance. Battery packs would be strategically attached to the undercarriage of the train in a location that is both discrete, free from snagging, and still easily accessible. Also, the location identified to place the SHM system should be easily accessible during a regularly scheduled maintenance.

**Lamb-Wave Damage Detection**

To take advantage of the Lamb-wave technique, two sensors must be placed on either side of a possible damage location. In addition, an embedded system could be developed with the Lamb-wave technique to optimize sensor placement on the train. In a study conducted by Jinkyu Yang, et al. [10] an embedded PZT-sensor washer was created to fit between a base structure and connecting brackets to detect loose bolts. The configuration acts as an active system and produces promising results for loose bolt detection. A similar approach could be taken towards the Lamb-wave implementation on the train. An embedded system in the form of a washer or other small-embedded systems could be placed around bolts or other connections on the train. If the embedded sensors are robust enough, and depending on the optimal damage detection location, the sensors could be integrated into a semi-permanent fixture that allowed maintenance personnel to exchange a system during each maintenance period (e.g. connections between replaceable bolts). It is important to keep in mind though, that Lamb-waves are sensitive to geometry and material composition. Knowing Lamb-wave techniques work well on flat laminar surfaces, it is important to follow up on the ability of this technique to function with cylindrical and other varying types of geometry.

**Environmental and Operational Variability and Data Normalization**

The problem with detecting damage by comparing a signal from a potentially damaged structure to a baseline signal is that changes in the structural properties can be caused by means besides damage. For example, if the ambient temperature when the test signal was measured differed from the temperature when the baseline signal was recorded, a change in the structural properties of the assembly could be detected causing the SHM system to indicated damage when in fact no damage was present. Fortunately, intelligently selecting the time and location at which the measured signals will be recorded combined with some data normalization techniques can minimize the effects of the environmental and operational conditions present.
The trains on the Big Thunder Mountain roller coaster experience a large range of operational conditions throughout each day. Conditions such as acceleration, braking force, cargo loading and many more are constantly changing. To minimize the effect these conditions may have on the SHM system, the data used to detect damage should be taken once per trip around the track when each train is in the station and empty of passengers. While the station is the one spot on the track where the operational conditions are most consistent it is still possible that vibrations from external sources could cause false damage indications. To eliminate this possibility, the vibrations of the section of track in the station should be recorded along with the data from the train based SHM system. With this additional data a reasonable judgment can be made determining if the apparent damage reading is really a sign of damage or if excessive vibrations in the track could have caused it. If for example, a large truck happens to drive very close to the station at the moment when the SHM system is taking data, the acceleration reading from that track should show this and indicate that if any “damage” is detected that a second reading should be made to verify before the train is pulled off the track.

With the concern for operational variability covered by taking data measurements in the station and recording the local track vibrations, the primary environmental concern will be the affect of temperature on the SHM system. Research into the Lamb wave and impedance based damage detection methods has developed means to reduce the effects of temperature and therefore removing the necessity of taking temperature measurements for the purpose of data normalization as discussed below.

**Impedance Temperature Compensation**

For impedance based damage detection techniques, Park, et al., [12] showed that temperature greatly affects the electrical impedance measured at each frequency. This change in impedance is not surprising when the effects of temperature on both the dielectric constant of the PZT and the elastic modulus of the structure are considered. Park, et al. showed that the primary effects of changing temperature on impedance measurements was to shift a plot of the real part of the impedance verse frequency horizontally and to change the scale of the plot while maintaining the same general shape as shown in Figure 2. To counter this effect of temperature on the impedance measurements, Park, et al. replaced the real part of the measured impedance for the test case in equation 2 with:

\[
Re(Y_{i,2}) = \delta^T \cdot Re(Y_{i,2})_{measured} + \delta^S \quad (\text{Eq. 4})
\]

where \(\delta^T\) and \(\delta^S\) are coefficients calculated via an iterative process which minimizes the damage metric. Because changes in structural properties caused by damage drastically change the shape of the impedance verse frequency curve, the above normalization process will result in a relatively large damage metric when the structural changes are caused by damage, and a negligible damage metric when the structural changes are caused by temperature changes.
A study by Grisso, et al. [13] concluded that the primary effect of a temperature change on a longitudinal wave traveling in an aluminum structure was a change in the speed of the wave. Preliminary results by Sohn, et al. showed that temperature had the same effect on Lamb-wave speed in composite plates. Assuming temperature has the same effect on Lamb-waves traveling through the Big Thunder Mountain upstop wheel brackets it becomes apparent that using any type of time of flight analysis would be very challenging. Most likely such an analysis would require a normalization calculation based on the temperature of the material in question during data acquisition.

On the other hand, temperature appears to have minimal affect on the kinetic energy transferred in the center frequency of the waveform. Sohn, et al. showed that the shifting of the waveform caused by the change in speed had a negligible effect on the damage index calculated for a given actuator/sensor pair. This negligible effect is caused by the fact the DI is a measure of the attenuation of the waveform and not the time at which it was measured.

From the above studies, it appears that if the Lamb-wave based damage detection technique is to be used, then the DI calculation of equation 3 will provide for a robust system that is unaffected (minimally?) by temperature.

**Lamb Wave Temperature Compensation**

Figure 2: Effects of Temperature and Damage on Impedance Measurements

![Real Part of Impedance vs Frequency](Image)
Selection of Damage Detection Technique

In the case of the Big Thunder Mountain roller coaster, a SHM system that identifies the location of damage may be too extensive both quantitatively (not sure what you mean by quantitatively is this context) and financially. On the subject of quantification, it is important to look at which measuring technique provides enough data without unnecessary sophistication. With a dense enough sensor array, the Lamb wave technique provides a reasonable estimate of the damage location whereas the impedance based technique provides an indication of damage without any real ability to precisely locate that damage. In order to determine the most suitable measuring technique, the definition of damage must be reflected upon. The SHM system for the Big Thunder Mountain Roller coaster is primarily aimed at detecting loose bolts in the upstop wheel and floating axel along the under carriage of the train with the hope that supplemental damage such as tears or cracks to brackets and axels can also be detected. There is a bolted connection on either side of each cart holding up the floating axel upstop/guide wheel. Each connection is secured using two bolts. Each cart will have its own monitoring system, and because the impedance method only works over a small area, the impedance method should be able to narrow down the damage location to a specific bolted connection. The capabilities of a Lamb-wave based SHM system to locate the exact location of each loose bolt becomes unnecessary as the bolts in the connection can be rapidly inspected with the naked eye.

To make a further selection towards measuring techniques based on a quantifiable basis, the maintenance schedule of the coaster and availability of extra trains on standby must be considered. The current maintenance schedule is time based. Preventative maintenance is completed on each train every 72 hours. Once the 72 hours has expired, regardless of the trains use and/or condition, it is removed from the track for maintenance, which is conducted by maintenance crews that are on hand during regular amusement park hours. The Big Thunder Mountain roller coaster also has one or two trains (possibly more) that are placed on standby as surplus. Keeping this in mind, a “damaged” train, as indicated from an impedance-based SHM system, could be removed from operation immediately and maintenance crews could perform a damage inspection (as if on a normally scheduled maintenance cycle). Loose bolts can be quickly tightened or replaced. If other forms of visible damaged are discovered, say to brackets or the axels, these parts can be easily replaced, as they are small and inexpensive. In the interim, a standby train could be put into operation in less than 30 minutes to replace the damaged train. Ride operators could change out a damaged train without having to turn coaster enthusiasts away or completely shutting down the ride. In addition, the time saved between using an impedance based and Lamb-wave based technique is approximately 5-10 minutes, which, when compared to the number of bolted connections per cart (2) it becomes apparent that it is just as easy to use an impedance based technique to physically check for loose bolts as it is for a Lamb wave based technique to detect the location of the loose bolts. The Lamb wave technique does not add quantitative value to the SHM system because the impedance based method provides sufficient damage detection with less data collection and subsequent analysis. As for the preliminary cost of the hardware, the impedance-based technique also uses fewer sensors and requires less computational power.
After taking the technical capabilities and price comparisons of each damage detection technique into consideration, it appears the impedance-based method will be best suited for the Big Thunder Mountain roller coaster. While it doesn’t have the damage location abilities of Lamb-wave-based methods, the cost and computational power savings of the impedance-based method outweigh its shortcomings.

**Challenges and Issues**

Along with the challenges involved in determining the best damage detection process and which features to look for, there are several other issues that must be considered when designing a SHM system. These issues include economic pressures, liability, the effects of false indications of damage, hardware/software integration, and system verification.

**Economic Pressures**

*Bonding*

Adhesively bonding circuits and battery packs to the undercarriage of the train is the most economical method for securing the SHM system to the train. Adhesive bonding requires little to no modification to the train and it can be removed with chemical solvents or scraping tools. Bonding agents are commercially abundant and can be bought at inexpensive prices.

*Maintenance*

Economically, it may be more beneficial to have Disney engineers and/or the maintenance crews trained and certified to maintain the SHM system. Disney engineers are already familiar with the Big Thunder Mountain roller coaster and will need to become familiar with the SHM system regardless. The costs associated with using in-house engineers cuts down on the travel, food, and lodging expenses associated with bringing in an outside source. In addition, piezoelectric circuits are very inexpensive in bulk, and can be quickly replaced without the need for the SHM system manufacturer to make a trip to Disney. Cases involving a malfunction with a transmitter or receiver, though, may require the SHM system manufacturer to travel to Disney to inspect the system.

**Liability:**

Products liability refers to the liability of any or all parties along the chain of manufacture of any product for damage caused by that product. This includes the manufacturer of component parts (at the top of the chain), an assembling manufacturer, the wholesaler, and the retail store owner (at the bottom of the chain) [14]. Disney, in the event of an accident resulting from the failure of the SHM to warn of adverse conditions, could hold the manufacture of the SHM system, and their constituents liable. The chain of parties involved in liability could include the maker of the SHM operating system, hardware manufacturer, maker of piezoelectric circuits, manufacturer for batteries and adhesive bonding material, etc… However, the real direction for liability depends on Disney’s involvement with the implementation of the SHM system.
The more responsibility Disney takes on for implementing the SHM system for the Big Thunder Mountain roller coaster, the more liability they can incur. Disney could avoid liability issues by hiring the maker of the SHM system to install and test the system for each train. Makers like Honeywell-Sensotec will handle a system’s integration. If abnormalities resulting in a catastrophic event occur from the time the system is initially installed, Disney has a better chance of claiming compensation from the SHM manufacture and/or their constituents. If Disney can claim that they had no impact on the anomaly, they may have a better chance of proving that the SHM system product was defective by design and/or manufacture, and possibly marketing as well.

The next step that Disney will have to take into account is the fact that the SHM system will have a life cycle and circuits, batteries, software, and even computing hardware will need to be replaced at some point. Disney maintenance crews could be trained, even certified if necessary, to replace circuits and batteries. Disney personnel, depending on how autonomous the system is, could perform software upgrades. An engineer on call at the park at all times could easily maintain the software capabilities and ensure the system is functioning reliability and appropriately. Disney could reduce liability, in the case of an adverse event, by proving they were following protocols and specifications by having an engineer on hand and showing their maintenance crews are certified/trained.

**Effects of false indication of damage:**
An important consideration when implementing the SHM system is the factors of false-positive and false-negative results. False-positive results can cause a train to be unduly removed from the track causing a hold up to coaster enthusiasts and lost time for maintenance crews. If a train on standby is not fully operational and cannot be applied to the track, ride operators will be one train short causing longer lines to patrons. Although time consuming, the effects of false-positives results little in lost dollars and does not pose a safety threat. False-negatives are much harder potential losses to absorb. A false-negative can cause a catastrophic failure to be ignored resulting in the loss of lives. In order to meet these potential flaws, a rigorous analysis of the software system used in the SHM system will need to be performed, before implementation, to determine the confidence levels of the system. *(May run the system in parallel with current procedures for awhile until confidence is gained)* The SHM system for the Big Thunder Mountain roller coaster would ideally be designed to give undamaged readings with a 95% confidence level or less. Assuming the damage matrix distributions for the damaged and undamaged situations overlap, higher confidence levels any higher then this run the risk of producing more of the potentially deadly false-negative readings.

**Hardware/software integration:**
In order to integrate computing hardware, the systems software needs to be determined first. Matlab can meet the data acquisition and data analysis needs in conjunction with the piezoelectric circuits and computational cores. Also, Matlab is a software package that can be used on just about any commercial hardware on the market today. Wireless *Telemetry* will be used for the hardware on the roller coaster and can easily interface with Matlab. Also, as technology progresses, better forms of statistical analysis may be discovered and faster, smaller forms of computational cores and Matlab
capabilities may be established. In the case of technology advancements, in both hardware and software, upgrades can easily be introduced to the SHM system through the replacement of individual elements or possibly through a new SHM system.

**Verifying damage detection capability**

The impedance based measuring technique is temperature sensitive. Special consideration must be given to normalize the temperature impact on the electrical impedance at each frequency so the SHM system can operate on a reliable level, and also to help reduce the amount of potential false-positive and false-negative results. As mentioned previously, Park, et al. are able to counter the effect of temperature by replacing the real part of the measured impedance for the test case with coefficients calculated via an iterative process which minimizes the damage metric. Normal weather in Anaheim, CA is mild, with little temperature fluctuation during the summer and winter months. However, on days with enough temperature change to impact the electrical impedance, a test of the SHM will need to be performed to verify the systems detection capabilities. This test can be done when each train is in for preventive maintenance. A “supervised learning approach can be taken by tightening and loosening bolts on one or several of the trains and their connecting carts to acquire baseline data and ‘damaged’ data. Each train can be tested in the morning, afternoon, and evening when temperature changes are most extreme and a comparison between the baseline and damaged data can be made. Also, to maintain a control of processes over the SHM system, measurements can be compared from trains during the hottest and coldest days of the year.

Regularly scheduled SHM system verification can be performed on a weekly basis (fewer/longer intervals will depend on the reproducibility of the actual SHM system). The verification can take place during preventative maintenance after the train has been serviced. Testing will include the loosening and tightening of bolts. If the temperature is consistent, then verification can be performed at least once, depending on the results of the analysis.

**Summary**

While it would be a considerable challenge to implement a structural health monitoring system on the Big Thunder Mountain roller coaster, careful consideration of every aspect of the SHM systems design should result in a safe, reliable system. The cost and life-savings capabilities of the proposed SHM system will more then pay for its self as well as provide both Disney and its costumers a strong sense of safety. Based on careful consideration of the environmental and operational variability, data acquisition challenges, damage detection techniques, and the ability to reliably identify a system as damaged we believe the proposed impedance-based damage detection system will prove to significantly reduce the potential for injury on Big Thunder Mountain.
References


