A Structural Health Monitoring System for the Big Thunder Mountain Roller Coaster

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On Sept. 5, 2003, an accident on Big Thunder Mountain lead to one death and 10 injuries.

After 50 min. of service, both bolts holding up the left side of the floating axel/upstop wheel assembly on the engine of train 2 had worked themselves out.
On Sept. 5, 2003, an accident on Big Thunder Mountain lead to one death and 10 injuries.

On the Subsequent Trip around the track:
- Floating axel shifted, dropping right wheel
- At entrance to tunnel, wheel hit brake and damaged a brake sensor
- Axel assembly then became wedged between a railroad tie and brake
- Rear of engine began to lift
On Sept. 5, 2003, an accident on Big Thunder Mountain lead to one death and 10 injuries.

As rear of engine lifted:
- Front of engine hit brake system on track
- Towbar connecting car 1 failed
- Car 1 collided with underside of engine – resulting in fatality
- Engine became wedged between roof of tunnel and track
To reduce potential for such accidents, we propose a monitoring system for Big Thunder.

Today's Presentation will cover:

Benefits of implementing a Structural Health Monitoring System

Damage definition and detection techniques

Techniques to minimize effects of environmental and operational variables

Implementation procedures
Current maintenance schedule is time-based and prone to human error.

- **Routine maintenance every 72 hours**
  - Colored Tags indicate status of train
  - Managers sign-off completed work
    - After Accident, procedure changed, so work must be signed off by Machinist as well
A Structural Health Monitoring (SHM) system will reduce number of injuries and save money.

- Historically Amusement parks are very safe
  - 2001 Study found 1 in 24 million chance of serious injury[1]

- However, It just takes a few accidents:
  - 24 passengers have been injured on Big Thunder since 2001
    - Litigation cost for each injury in the millions of dollars
    - Increased insurance rates
    - Decrease in patron confidence

- Additional savings possible by moving to condition-based maintenance
A successful SHM system should be able to detect: 1) loose bolts, 2) cracks, 3) corrosion

- Bolts loose enough that boundary conditions altered
- Cracks larger than the critical crack length (estimate: 0.5 cm)
- Corrosion that reduces the fatigue limit below anticipated stress levels
Impedance and Lamb-wave based damage techniques were considered.

**Impedance-based method [2]**

- Relies on coupling between electrical impedance of a piezoelectric patch and mechanical impedance of structure
- Requires a sinusoidal electrical input ranging from 30 to 250+ kHz
- Can only detect damage over a limited area
Impedance-based damage detection

For Impedance method, damage quantified by damage metric \( (M) \)

\[
M = \sum_{i=1}^{n} [\text{Re}(Y_{i,b}) - \text{Re}(Y_{i,d})]^2
\]
Lamb-wave-based damage detection

- Detects damage in Plate-like structures
- Two or more PZT patches:
  - One patch acting as an actuator
  - One patch acting as a sensor
- Can travel long distances and cover large areas
- Complete ‘picture’ of structure can be developed
- Sensitive to Geometry and Material Composition
- Two techniques

Piezo sensors in pulse-transmission mode to detect energy present at driving frequency
Lamb wave damage detection technique 1: Time of Flight Comparison

- Measures the time it takes a waveform input (actuating PZT) to reach a sensing PZT.
- Conclusions can be made on how the structural properties of the material have changed.
- Temperature affects speed of traveling waveform.

Image from Sohn, et al. [3]
Lamb wave damage detection technique 2: Kinetic Energy Comparison

- Compares the kinetic energy of the waveform received by the sensing PZT [3]

Damage Index:

\[ DI = 1 - \int_{u_0}^{u_1} Wf_t(u, s_0)^2 du \div \int_{u_0}^{u_1} Wf_b(u, s_0)^2 du \]

where \( Wf(u, s_0) \) = is the wavelet transform, subscript \( t \) represents the test case while the subscript \( b \) represents the baseline signal.

- Wavelet transform is taken at the center frequency of the input waveform (supplied by the actuating PZT)

- Temperature has minimal affect on kinetic energy transferred in the center frequency of the waveform
Operational and environmental variability must be accounted for to ensure reliability.

**Environmental Variables**
- Temperature, weather (rain, wind, etc.), external vibrations (nearby construction, earthquakes) …

**Operational Variables**
- Velocity, Acceleration, Load (number of passengers), bearing quality, number of trains on track …

Many of these operational variability's can be avoided by taking data when trains are in the station with no passengers.
External vibrations can be accounted for by measuring vibrations of track in station.

- Outlier analysis increases reliability of system
  - If a measurement with a large damage metric corresponds to large scale track vibrations - Repeat Measurement
Iterative calculation accounts for temperature changes in the impedance method

A change in temperature causes a change in scale and a horizontal shift in the impedance vs. frequency plot

Replace impedance with: \[ \text{Re}(Y_{i,2}) = \delta^T \cdot \text{Re}(Y_{i,2})_{\text{measured}} + \delta^S \]
Iterative calculation accounts for temperature changes in the impedance method cont...

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

\(\delta^T\) and \(\delta^S\) are coefficients which minimize the damage metric.

Changes in structural properties caused by damage drastically change the shape of the impedance versus frequency curve.

Structural changes caused by damage result in a relatively large damage metric using the normalized equation above.

Negligible damage metric when structural changes are caused by temperature changes.
Lamb wave temperature compensation for techniques 1 and 2

**Technique 1: Time of Flight**

- primary effect of temperature change on a longitudinal wave is a change in the speed of the wave.
- Need to perform normalization calculations based on the temperature of the material in question during data acquisition.
- Challenging to use this technique

**Technique 2: Kinetic Energy**

- Sohn, et al. [3]: shifting of the waveform caused by change in speed [temperature] has negligible effect on the damage index.
- damage index is a measure of the attenuation of the waveform and not the time at which it was measured.
Impedance-based method chosen over Lamb-wave-based damage detection

- Very sensitive to small changes
- Requires less sophistication
  - One PZT instead of two or more
  - Sufficiently able to locate damage
    - Identifies bolted connection/structural member that is damaged

![Diagram of Upstop Wheels, PZT Patch, and Wheel Bracket]
Implementation of the SHM system: wired vs. wireless

**Wired System**
- Cannot provide real-time data
- Wires spanning a train must allow for slack
- System most effective if used once or twice daily

**Wireless System**
- Provides real-time data
- Don’t need to dock system
- System can monitor as needed

Low-powered battery system can be used for both systems
A wireless structural health monitoring system will be implemented on Big Thunder. The system’s hardware includes:

**Strain/acceleration sensors**
- Piezoelectric (PZT) sensors placed on bolted connections of each cart

**Computational core**
- One 32-bit Motorola MPC555 PowerPC microcontroller per cart

![Diagram of the system](image-url)  
*Figure 2 – Architectural design schematic of proposed wireless sensing unit*
A wireless structural health monitoring system will be implemented on Big Thunder. The system’s hardware includes:

- **Wireless transmitter**
  - One wireless transmitter per train (6 carts)

- Honeywell Sensotec currently makes a Model 2116S wireless transmitter and a Model 2145A receiver, possible modification for Big Thunder

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Image of wireless system used by Lynch, et al. [4]
A wireless structural health monitoring system will be implemented on Big Thunder. The system’s hardware includes:

◆ **Batteries**
  - NiMH or lithium-ion batteries do not exhibit ‘memory effect’

◆ **Station mounted computer**
  - Matlab can easily perform data analysis
  - Easy for operators to see status of train

![Graphs showing electrical impedance measurements of PZTs at Junction D.](image)

Figure 3. The electrical impedance measurements of PZTs at Junction D. The variation in the impedance is increased as the level of damage is increased: (a) 2 bolts loosened, (b) 4 bolts loosened, (c) 6 bolts loosened, (d) 8 bolts loosened.
False positives/false negatives, and system verification

- **False negatives** – Damaged Train continues to operate on track
  - Life safety concerns
  - Renders SHM system useless

- **False positives** – Require trains to be pulled off track when in fact they are undamaged
  - Increased waiting time for patrons
  - Time loss for maintenance workers

- Verification performed during preventative maintenance by loosening bolts/measurements taken morning, noon, evening to compensate for temperature
In Conclusion: An impedance based SHM system will increase patron safety and decrease the cost of operating Big Thunder.
References

[1] “White Knuckles are Worst of it”.

