ANALYZING THE DYNAMICS OF HIGH SPEED RAIL

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Motivation

• Rail is a very attractive technology for moving people and goods
  • Suspension system is extremely energy efficient
  • Guidance system allows for all-weather operation
• However, its suspension system is also a source of great challenges in terms of:
  • Ride comfort
  • Wear and tear on the vehicle
  • Maintenance of the track / guideway
• Hence, it is important to design a suspension and guidance system which is smooth, quiet, and disturbance-free
Challenges

• System has lots of moving parts
  • Flanges, primary and secondary suspension, bogies (trucks) that turn on both ends of the car
  • Lots of non-linearity, very difficult to model and analyze, very difficult to create a good control system

• Most system engineers
  • Linearize the systems they study, treat with linear models, approximate the solution

• But with rail this is not possible to do
  • Springs and dashpots enter and leave the system
  • Spring and dashpot rates vary for the interfaces that are always present
  • Resonant frequencies can change dramatically; so can the time constants
Design Options

• Four options exist for design experimentation
  • Full scale, scale models, math analysis and simulation
• Historically, the options were scale and full-scale testing
• Advent of calculus made the third possible
  • Closed form solutions to differential equations
  • Resonant frequencies, eigenvalues, damping ratios
  • But it only works with linearization assumptions
  • All control theory is based around linearization
• Advent of the computer made simulation possible
  • The realism of the real-world system can be incorporated
  • But the design process is complex and time consuming
Simulation

• Large computing capability required
• Very large number of state variables involved
• Massive memory for storing the status quo
• Very small time steps may be required (surprisingly small)
Remainder of the Presentation

• Provide some insight as to why the system is challenging to model
  • Sources of the inputs that create the challenges
  • Representing them in a simulation model
  • Predicting the performance using step functions and actual track geometry inputs
  • Iterating toward design success

• Show how the process unfolds and results obtained
The Track is the Input Source

Train movements occur as train moves over the track

- Forces, accelerations, speeds, displacements
- Lateral, vertical, longitudinal
- Yaw, roll, pitch

Many factors affect these dynamics

- Track geometry and maintenance
- Rail and wheel profiles
- Train speed and handling
- Train consist, placement of cars, etc.
Track Geometry

- Deviations in geometry accentuate the dynamics
- Deviations caused by
  - Vertical or horizontal kinks
  - Mismatched, bent or battered joints
  - Worn points
  - Battered frogs & crossing diamonds
  - Poor cross-level
    - Rock & roll
  - Tight or poorly aligned spirals
    - Warping in the track geometry forces suspension diagonally to limits
    - Binding side bearings keep trucks from turning
Track Geometry Forces

- Lateral force dynamics caused by changes in alignment & gage
  - Wide gage > truck hunting at high speeds
  - Tight gage > truck hunting at low speeds
- Vertical force dynamics caused by
  - Changes in cross-level, superelevation and profile
  - Vehicle axis rocks about the center of gravity
  - Produces horizontal component at the rail because of the shift in center of gravity
HSR Vertical Geometry

TOP: Paris - Lyon, profile along old PLM line

BOTTOM: Paris - Lyon, profile along LGV Paris Sud-Est

Source: Chemins de Fer Magazine (AFAC)
Wheel-Rail Interface is the Source

New Wheel & New Rail

New Wheel & Worn Rail

Worn Wheel & Worn Rail

Worn Wheel & New Rail

Contact Angle Simulation
Effects of the Interface

- Because of the small contact area and the weight of the load, complications are inevitable.
- Wheel and rail wear result, plus noise, formation of martensite, cracks in the rail, corrugation.
Very Small Contact Area

The weight of the train is placed on a very small surface area of the wheel that makes contact with the rail.

Location of the wheel/rail contact patch is here in this picture
Forces In Curves

- Difference in distance rolled by outside versus inside wheel
- Effect of conical wheel tread
- Creep forces
  - Cause truck to steer to curve outside
  - Magnitude of forces depends on gage, corrugations & geometry
- Lubrication mitigates forces (but interferes with steering)
Vertical and Lateral Forces

**Vertical**
- Vehicle weight
- Unbalanced elevation in curves
- Car/locomotive dynamics
- Track geometry input
- Coupler forces

**Lateral**
- Flanging force
- Centrifugal force
- Frictional curving force
- Coupler force
- Buff & draft force
- Truck hunting
- Track geometry force

Full-Scale Video
Scale Model Video
Potential Dynamic Impact

French HSR run
go to 1:19
L/V Ratio

- Ratio of the lateral force to the vertical force
- Lateral forces steer the truck
- Vertical forces support the train weight
- Wheel/rail profile affects the vector addition of these forces
- Affects stability
  - Hunting (lateral)
  - Wheel lift (vertical)
Critical L/V Ratios

- **L/V ≥ 1.29**
  - Wheel may climb new rail.
- **L/V ≥ 0.82**
  - Wheel lift may occur
- **L/V ≥ 0.75**
  - Wheel may climb worn rail.
- **L/V ≥ 0.64**
  - Rail overturn may start
  - Poorly restrained rail may rotate away from wheel
Centripetal (Centrifugal) Force

OVERBALANCE

EQUILIBRIUM

UNDERBALANCE

Superelevation

Centrifugal Force

Center of Gravity

Gravity

Resultant

Centrifugal Force

Center of Gravity

Gravity

Resultant

Amount of Underbalance

\[ V_{\text{max}} = \sqrt{\frac{E_a + 3}{0.0007 D}} \]

\( V_{\text{max}} \) = Maximum allowable operating speed (mph).

\( E_a \) = Average elevation of the outside rail (inches).

\( D \) = Degree of curvature (degrees).
Hunting

Caused by:

- Empty or lightly loaded cars (though heavy cars can also hunt).
- Train speeds above 45 mph.
- Dry rail.
- Three piece freight car truck.
- Roller side bearings.
- Tangent track or curvature of 1 degree.
- Roller bearing wheelsets.
- Worn wheel treads having a hollow appearance over good quality track.
- Poor vertical snubbing.
Center of Gravity & Oscillation

• High center of gravity cars & low joints at truck spacing is the worst
• Rocking magnifies alternate rocking on other rail
  • Wheel lift on successive joints
  • Especially dangerous on curves
• Resonance occurs at critical speed
• Critical speeds occurs at multiples of frequency & wavelength
Bounce and Pitch

- **Bounce**
  - Increase & decrease vertical loading
  - Speeds > 40 MPH
  - Change in track modulus

- **Pitch**
  - Varying vertical load transfers end to end
    - Square joints
    - Wheel climb & short flange marks

Bounce & pitch result of surface variations

Bouncing train
High Speed Wave Propagation

\[ c_T = \sqrt{\frac{G}{\rho}} \]

\[ \frac{W_{\text{dyn}}}{W_{\text{stat}}} = \sqrt{1 - \left(\frac{V}{V_{\text{cr}}}ight)^2} \]

Graph showing vertical displacement vs. running speed.
France TGV World Speed Record
Trucks, Suspension, Traction Motors
Pantographs and Couplers
Modeling the System

- Select a level of detail
- Define the individual masses
- Specify weights, moments of inertia
- Define the interfaces
- Specify the spring rates, dashpot rates, physical geometry
- Define the inputs
- Conduct the simulation
- Analyze the results
- Refine the model and repeat
Defining the Interfaces

- Type
- Physical geometry
- Spring and dashpot rates
Analyzing the Results

- Nominal new condition
- Initial lateral offset
- P, Q, R: Lateral front, middle, rear axles
- N: Longitudinal, rear
Effects of Condition Change

- Worn pedestals
- Same initial lateral offset
- P, Q, R: Lateral front, middle, rear axles
- N: Longitudinal, rear
Standard 3-Piece Freight Car
3-Piece Freight Car with Steering
LRC 2-Axle Locomotive
Modeling Results

Position Trends

Force Trends

Yaw and Roll Trends

L/V Ratio Trends
Scale Models
Full Scale
Field Test
Viewing Performance
Full-Scale In-Service Equipment
Derivative Designs
Questions / Discussion