Monorail Las Vegas

Drive Train Investigation
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Las Vegas Monorail – USA

- Fully automated, driverless system
- 6.4 km elevated dual-monorail guideway
- Maximum grade: 6.5%
- Guideway-mounted power rails
- Links eight major resort properties and the Las Vegas Convention Centre
- Seven stations
- Nine four-car trains
- Passenger capacity: 3,200 pphpd
- In revenue service since July 2004

Consortium full turnkey design, build, equipment. Bombardier design and supply of E&M equipment, systems engineering and integration, project management, testing and commissioning.
Las Vegas Monorail
Problem Description and Interim Solution

- **Noise problem („Growling“)**
  - Noise
    - During acceleration & braking
    - In motor cars only
    - Modification of motor converter & control did not solve the problem

- **Root cause & interim solution**
  - High angle of load arm and cardanic shaft was determined as root cause
  - Interim solution: Load arm rides between stations/platforms at safety link
  - Motor moved 1“ outwards
    - Only small angles of cardanic shaft
    - Significant reduction of noise (and loads)

- **Potential of possible solutions had to be figured out**
### Train Configuration

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
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</thead>
<tbody>
<tr>
<td><strong>Load Wheel</strong></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td><strong>Guide Wheel</strong></td>
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<td><strong>Steering Wheel</strong></td>
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<tr>
<td><strong>Disc Brake</strong></td>
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<tr>
<td><strong>Motor &amp; Gear</strong></td>
<td></td>
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</tbody>
</table>
Drive

- Motor
- Planetary Gear
- Brake Disc
- Bevel Gear
- (Cardanic) Drive Shaft
- Load arm
- Spring
- Guide Wheel
- Load Wheel
- Planetary Gear
- Bevel Gear
- Brake Disc
- Power Rail
Drive
Drive Model

- **Simplified model**
  - Only one drive modelled
  - Guide wheels & steering mechanism omitted

- **Focus on rotating parts**
  - Load wheel
  - Planetary gear
  - Brake disc
  - Bevel gear
  - Cardanic shaft
  - Rotor

- **Properties of parts**
  - Partly valued on the basis of their geometry
Model Validation - Torsional Eigen Modes

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<th>No.</th>
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<th>Frequency</th>
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<td>15/16</td>
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<td>60.3</td>
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<td>17/18</td>
<td>0.04</td>
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- Motor out of phase with Brake Disc & Load Wheel
- Measured Frequency is ~ 58 Hz
Model Validation - Time Domain
Model Validation - Frequency Domain

- Test run 7b1
  - Mortlet Spectrogram
    - Gear Box Torque (left)
    - Drive shaft torque (right)
  - Measured values (top) compared to simulated ones (bottom)
Model Validation – Hammer Test

- Torsional input lever attached to the motor side yoke
Model Validation – Transfer Function

- Frequency Response Function - Load Wheel
  - Measured (blue, red) - and calculated (green) data fit well up to ~ 100 Hz
  - Some potential of further improvement may be seen
Integration of Flexible Bodies

- **NASTRAN model of Load Arm**
  - Guyan reduction
    - 30 nodes
  - Calculation of frequency response modes
    - 19 load cases added
      - 13 translational
      - 6 rotational
    - 8 load groups used with respect to maximum frequency of 1500 Hz
      - Problem: Lateral stability of load wheel/tyre
  - No geometric stiffening used
Eigen Modes in FE- and MBS-Model (1)

- FE, $f = 84.5$ Hz
- MBS, $f = 84.9$ Hz, $d = 1.4\%$
Eigen Modes in FE- and MBS-Model (2)

- **FE, \( f = 181.0 \text{ Hz} \)**
- **MBS, \( f = 189.1 \text{ Hz}, \, d = 0.9 \% \)**
### Eigen Modes in FE- and MBS-Model (3)

<table>
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<td>MBS-Model</td>
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<td>7</td>
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FEMBS- versus pure MBS-Model

Graphs showing load and displacement over time for different models and shafts.
Suggestion for improvement

- **Solutions to be investigated**
  - Torsional damper
  - Highly flexible coupling
  - Stiff/soft motor suspension
  - Constant-velocity joints instead of universal (cardanic) joints

- **Procedure of investigation**
  *(Example: Torsional damper)*
  - Extension of SIMPACK model by
    - Output (angular velocity)
    - Input (torque)
  - Linearization
  - Export state-space-matrices to MATLAB/SIMULINK environment
  - Investigation of observability and controllability
  - Adding the liner damper in MATLAB/SIMULINK
  - Calculation of pole-zero-map to identify properties of the damper
  - Refining the SIMPACK model
  - Investigation in time domain
Investigation in Frequency Domain
Pole-Zero-Map
Investigation in Time Domain

- **Investigation in frequency domain** shows high potential of improvement, especially for oscillation at 60 Hz
- **Investigation in time domain** did not confirm this expectation

**Problem**
- High moment of inertia required (similar to rotor)
- Space
- Well-tuned friction