Vibration and Acoustic Analysis of Trussed Railroad Bridge under Moving Loads

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Outline & Introduction

- Motivation
  - Denied Area Monitoring
  - Structural Health Monitoring
    - Battle damage assessment
- Structural Finite Element Model
  - Railroad bridge at Ft. Leonard Wood, MO
  - Transient response of structure due to vehicle loading
    - Brief description of implementation of moving load representation
  - Predict response due to different loadings
    - Axle speed
    - Axle weight
    - Single axle vs. Multiple axles (locomotive)
  - Model does not include effects of vehicle suspension
- Acoustic Finite Element Model
  - Include topography with ground impedance
  - Outputs of structural model used as inputs to acoustic model
  - Predict SPL (single axle)
    - Different frequency components
    - Different loading conditions
- Summary & Conclusions

Motivation

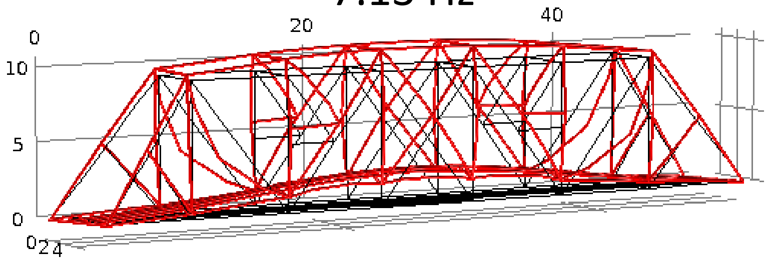
STRUCTURAL HEALTH MONITORING

- Battle Damage Assessment
- Remote assessment of structures for route reconnaissance
  - To complement satellite imagery
  - Scour usually not visible
- Significant changes in frequency response could indicate bridge instability

REMOTE TRAFFIC MONITORING

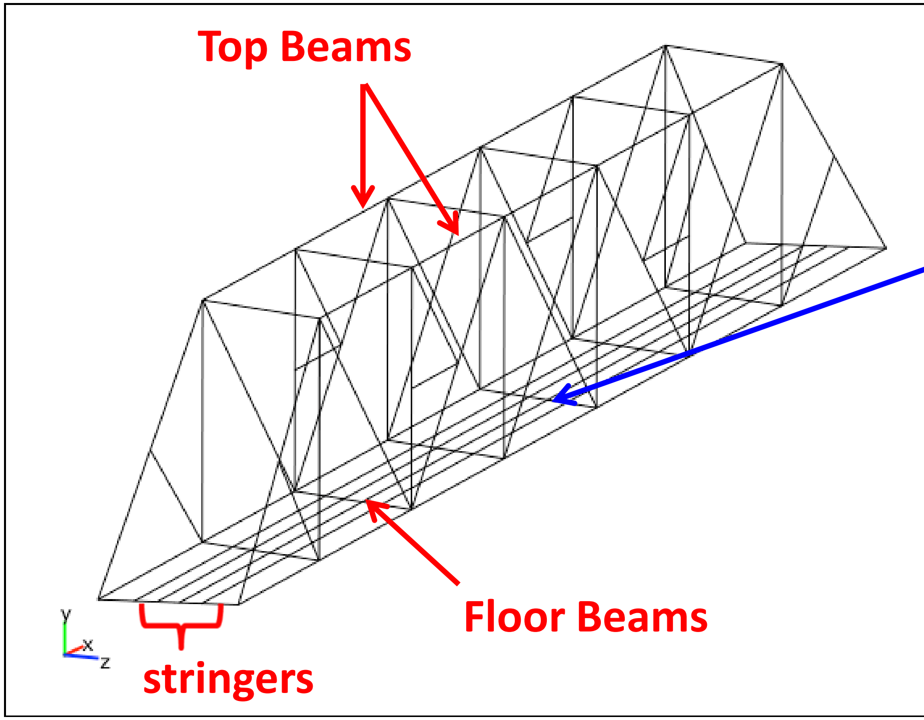
- Determine changes in traffic patterns
- Number and weight of vehicles
- Speed of travel

7.13 Hz



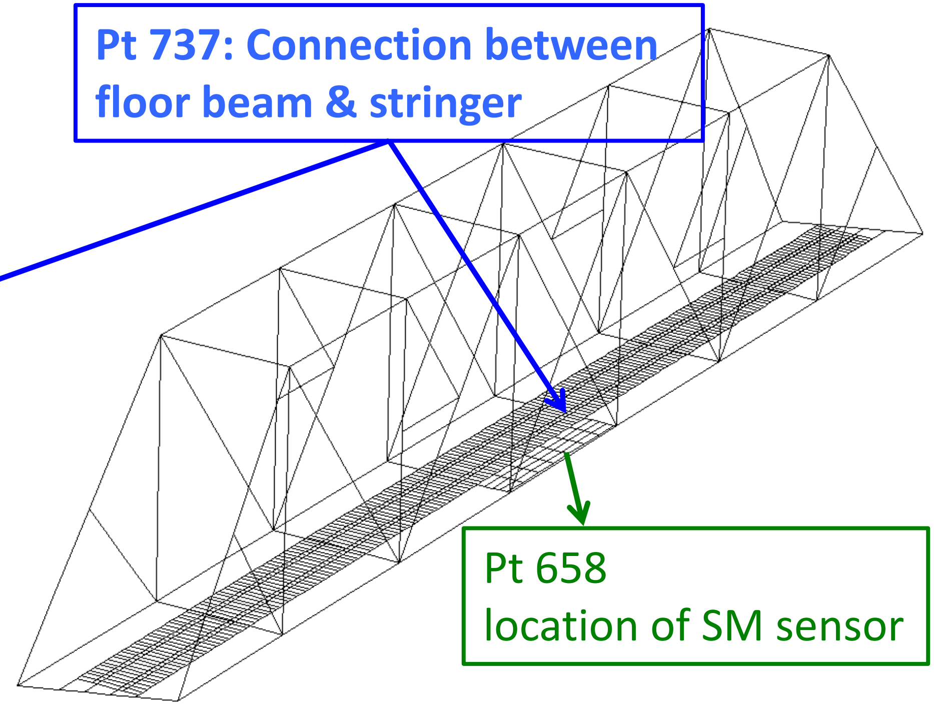
Structural Model

Anatomy of Ft. Leonard Wood Bridge



Truss bridge model

- 7 panel bridge
- 25° skew angle at ends of bridge
- Pinned at each end
- 3D Euler Beam elements
  - Material properties: E, ρ, ν
  - Cross section properties: A, I_{yy}, I_{zz}



Model with cross-ties & rails

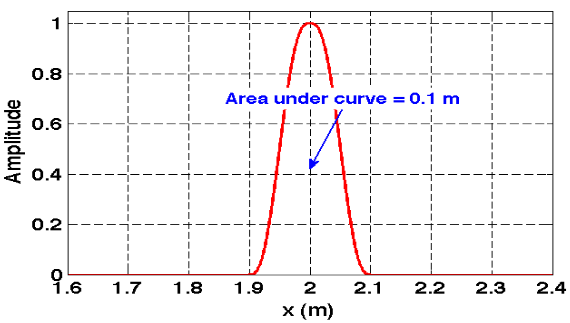
- Transmits load to structure
- Connections between crossties & stringers
  - Pinned – allows for more movement
  - Clamped – stiffer

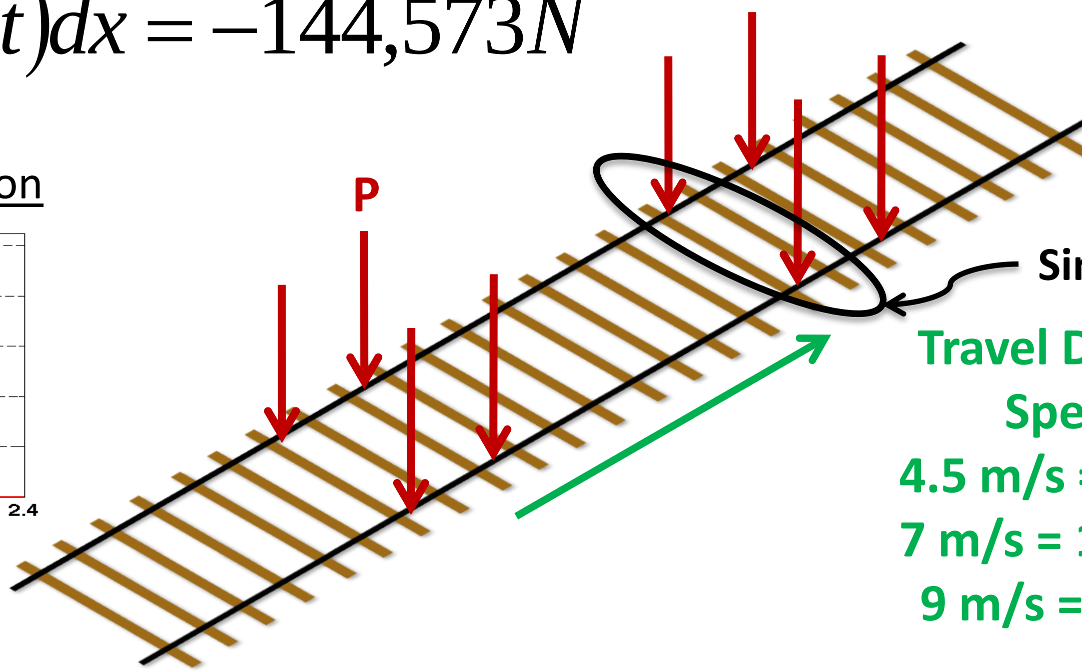
Traveling Load: Single Axle

- Single axle model
    - 2 wheels traveling across bridge at constant speed
  - Makes interpretation easier
- Locomotive model
  - Superposition of 4 single axle models with delays representing wheel spacings
- Traveling load distribution function represents concentrated load from each wheel
  - Verified formulation by calculating moving force on Euler Beams

$$P = \int F_0 \delta(x - vt) dx = -144{,}573N$$

Load Distribution Function





Travel Direction

Speeds:

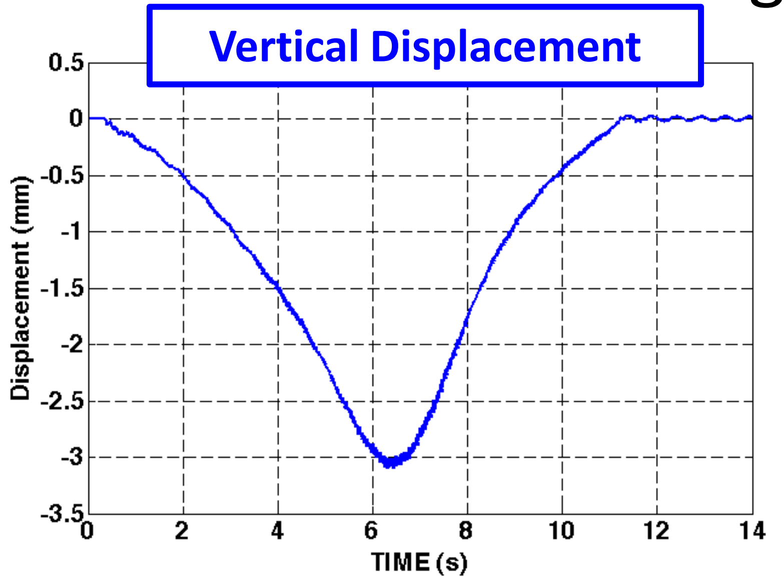
4.5 m/s = 10 mph

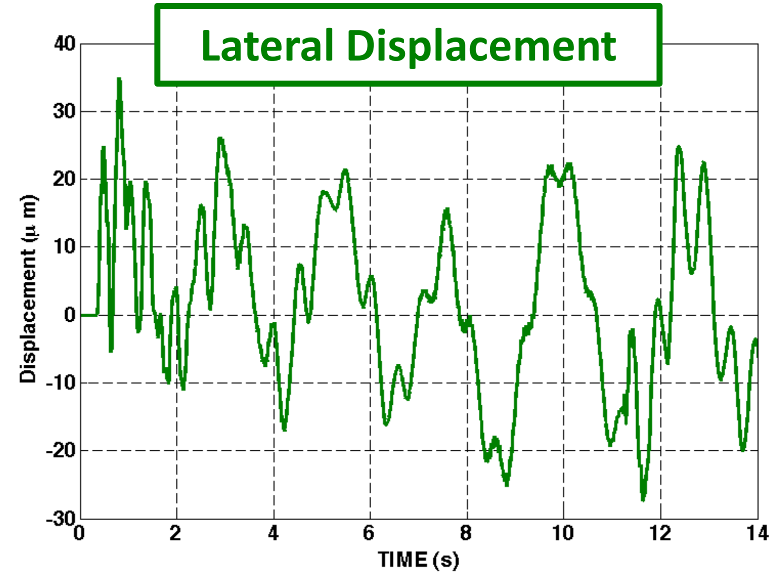
7 m/s = 15.7 mph

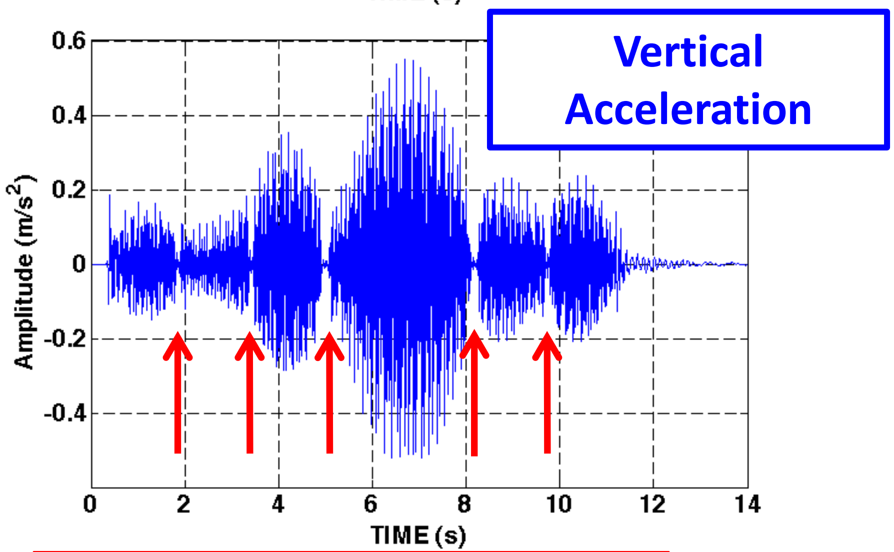
9 m/s = 20 mph

FE Results at Point 737

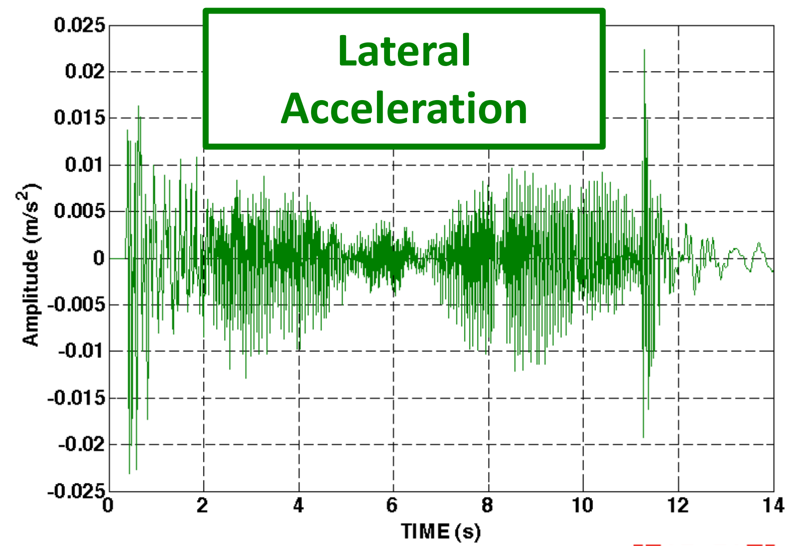
1 axle traveling at 10 mph (4.5 m/s)





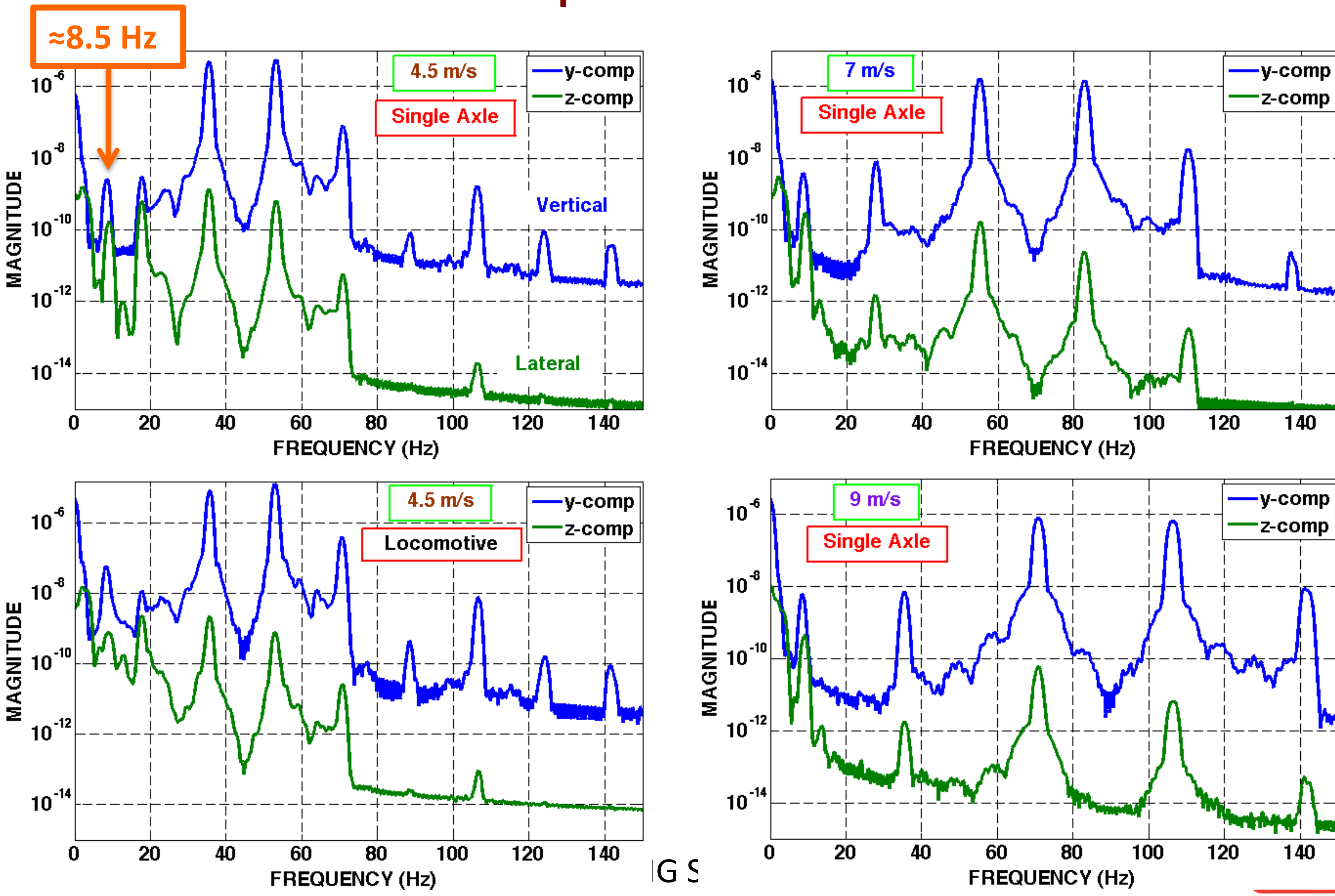


wheels crossing floor beams



Power Spectra: Point 737

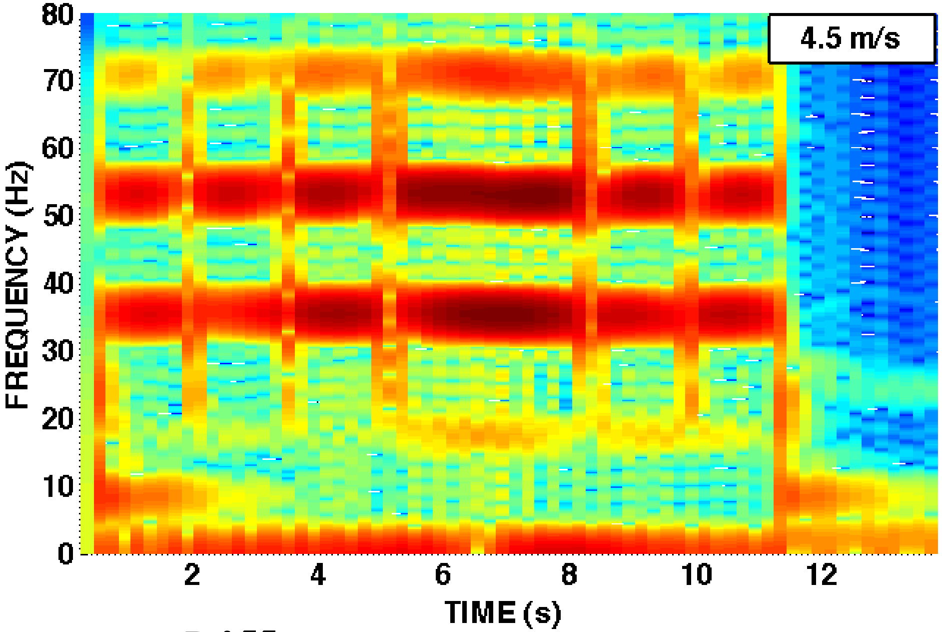
Effects of axle speed & number of axles



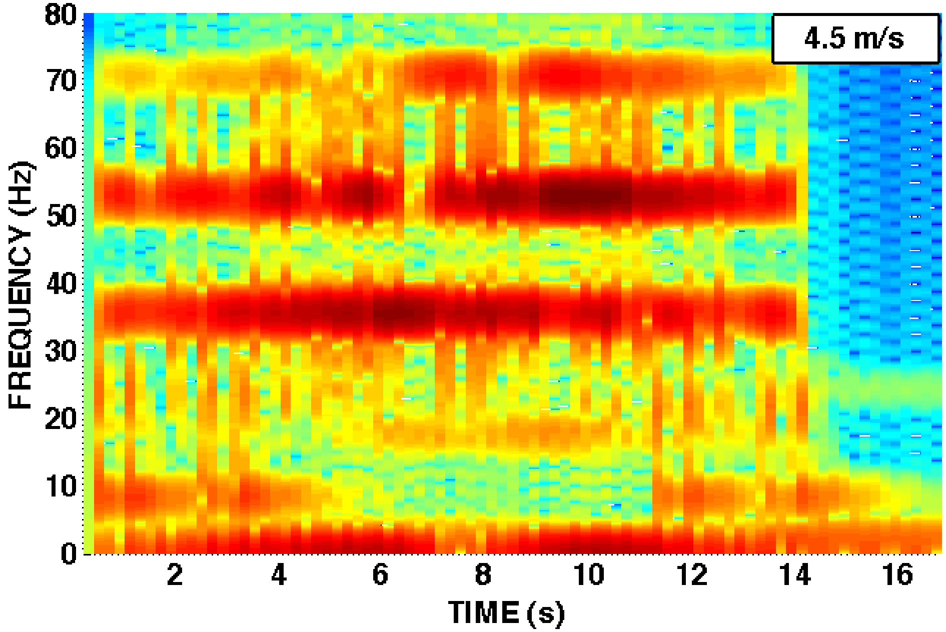
Effects of Adding Axles

Spectrograms from Particle Velocity near Center of Bridge

Single Axle

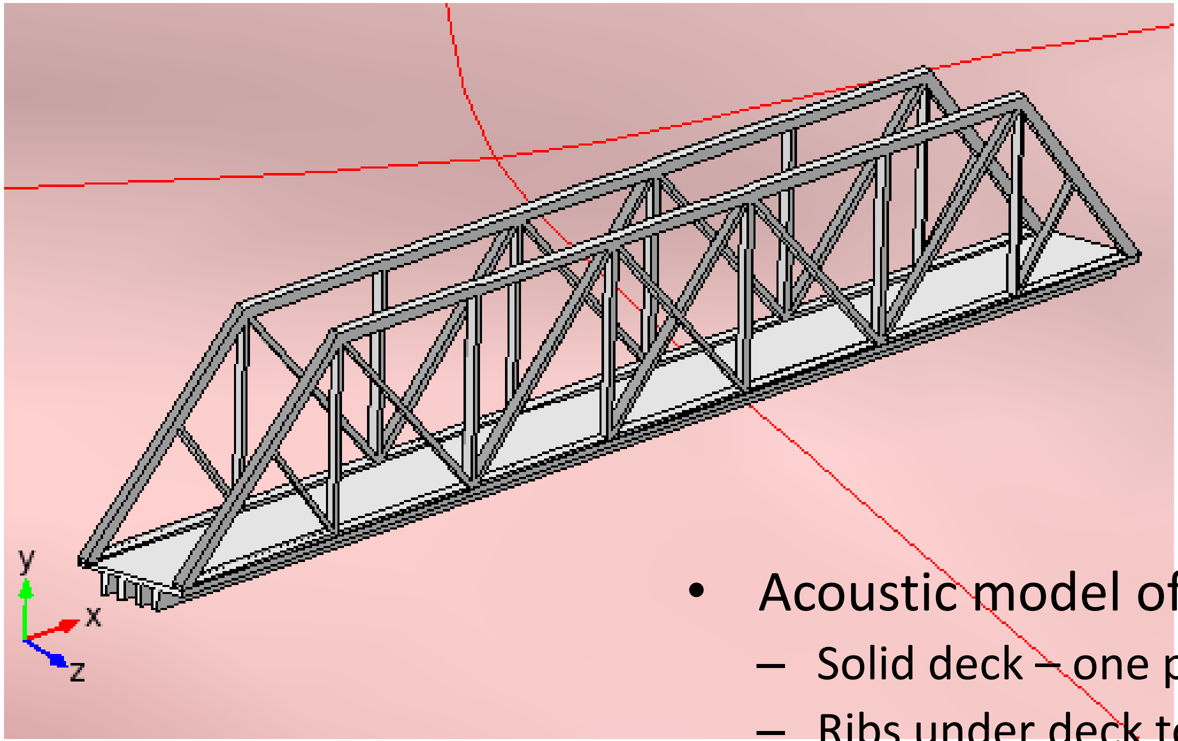


Locomotive with 4 Axles



- Differences:
  - broad-band response when axles cross Floor Beams
  - Engine takes a few seconds longer to completely leave bridge
- Similarities:
  - 2 and 8 Hz vibration as axle enters and exits bridge
  - 18, 36, 54, 72 Hz bands as axle crosses bridge

Acoustic Model of Bridge

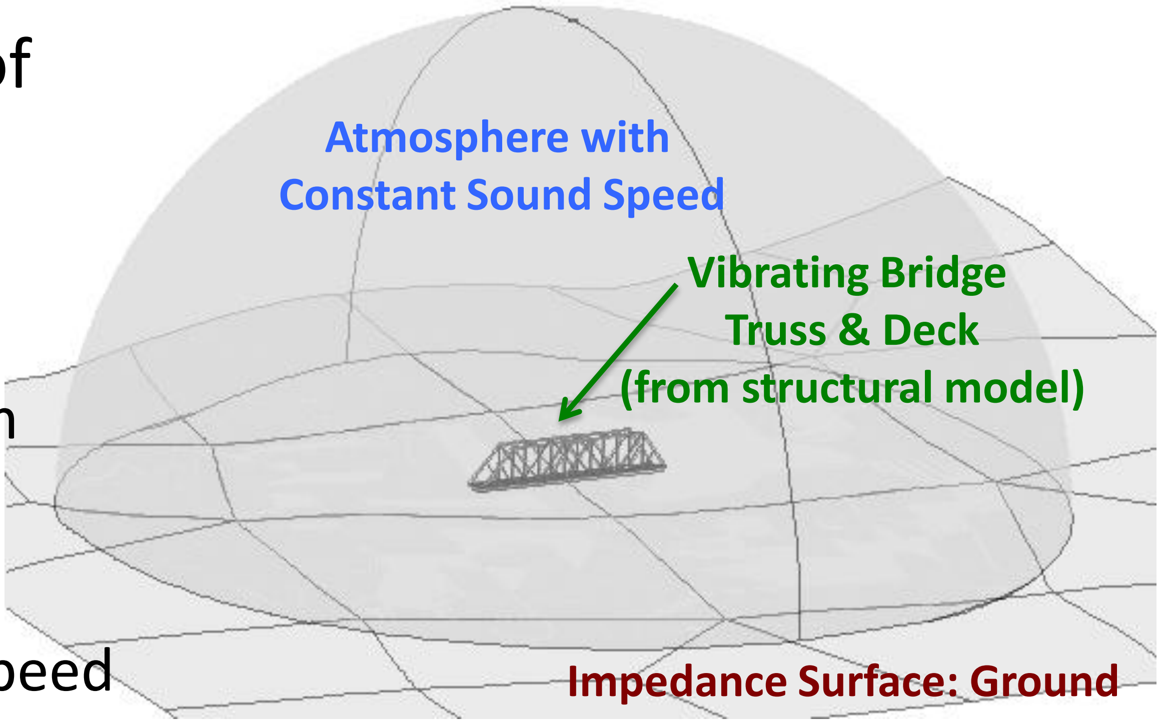


- Structural model
  - 3-D Euler Beam elements
  - Mechanical properties: ρ, A, E, I_{xx} & I_{yy}
  - No surface area to interact with surrounding fluid

- Acoustic model of bridge
  - Solid deck – one piece
  - Ribs under deck to represent stringers
  - Truss: extruded rectangular cross-sections
  - Bridge is 'empty' volume
    - Particle acceleration specified on boundaries

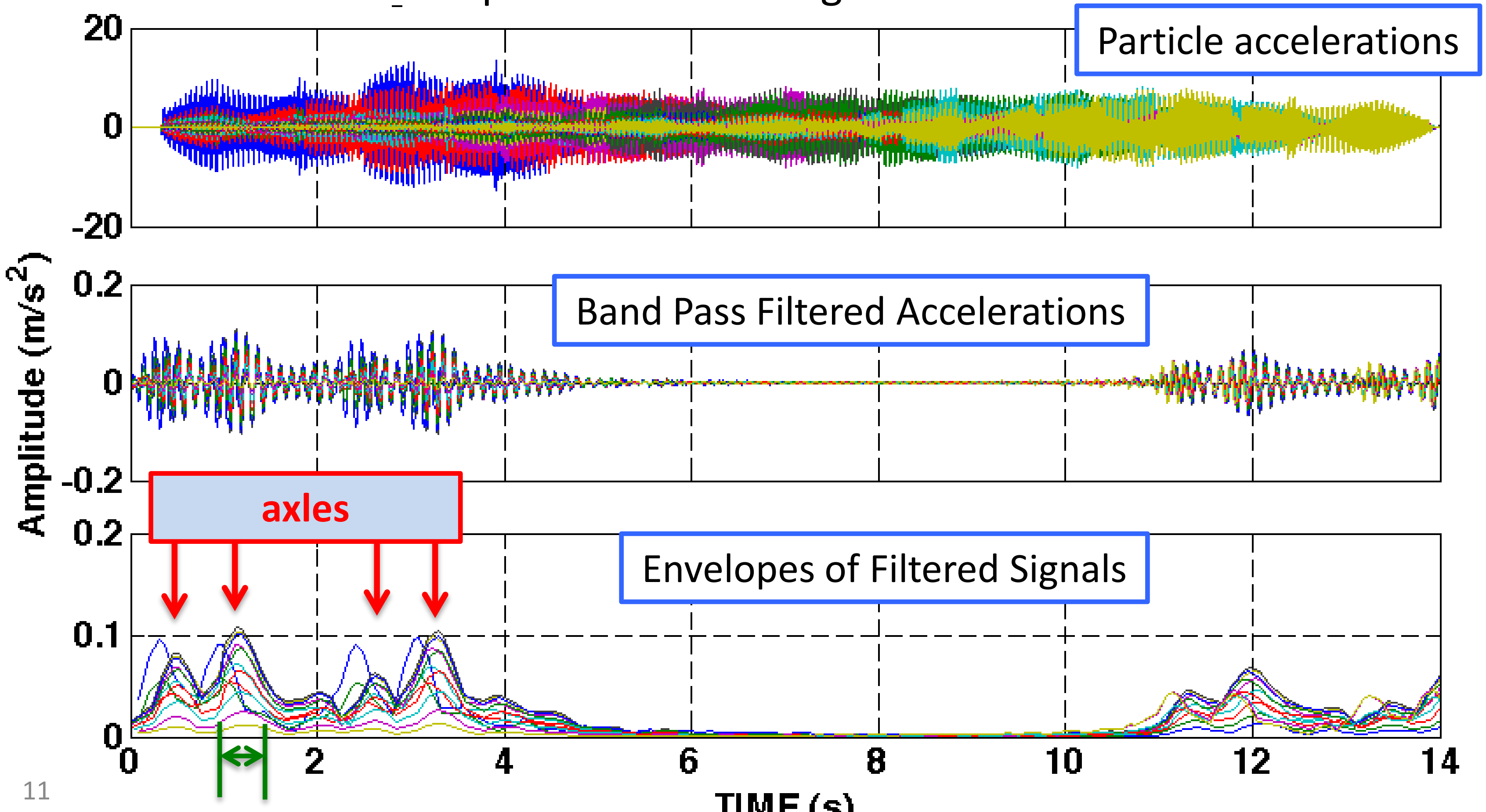
Complete Acoustic Model

- Three components
  - Acoustic model of bridge
  - Ground surface
    - From survey
    - Impedance of firm natural soil
  - Air atmosphere
    - Constant sound speed
    - Radiation BC

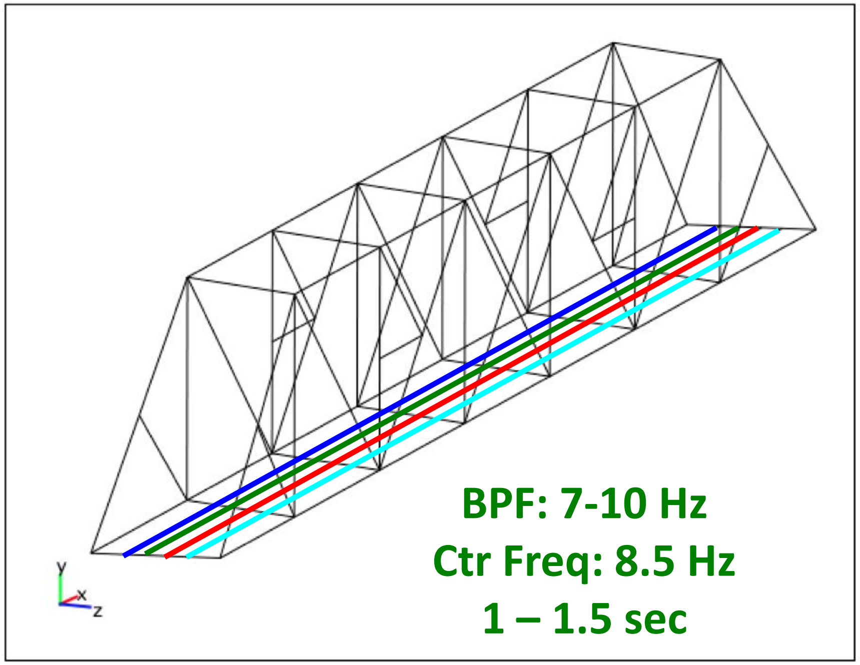


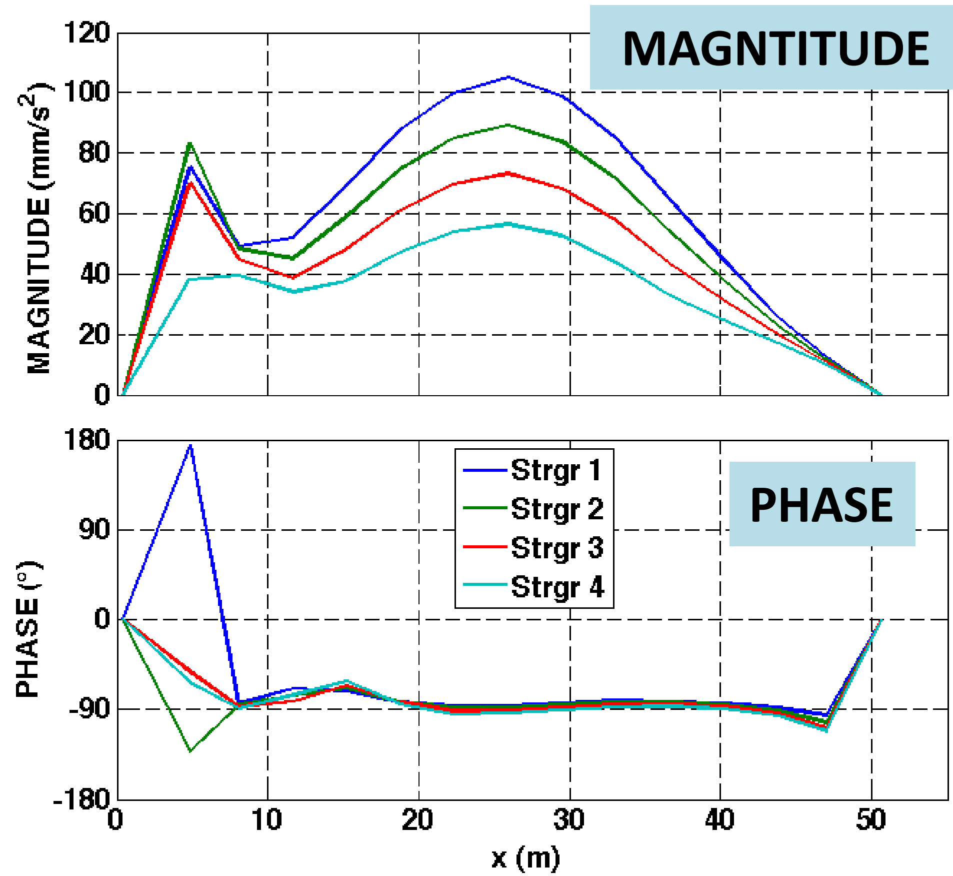
Filtered Accelerations from Structural Model

- Example: Vertical vibration of individual stringer
  - Locomotive traveling at 4.5 m/s (10 mph)
- Collect particle accelerations from points along stringer
- Bandpass filter: 7 – 10 Hz, Center frequency = 8.5 Hz
- Determine envelope from filtered signal



Acceleration Profiles

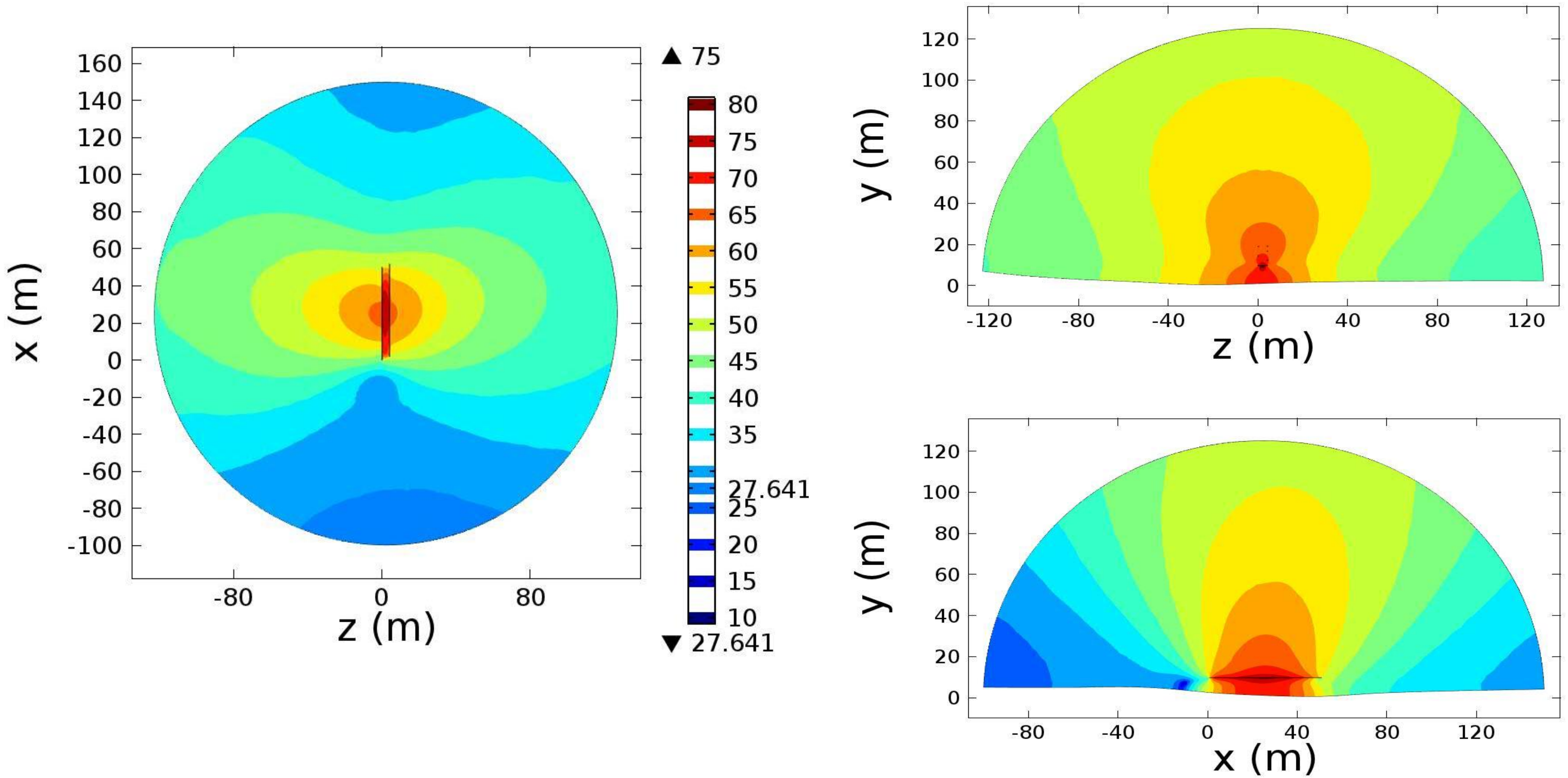




- Acceleration Profiles assembled for
  - vertical motion of bridge deck
  - horizontal motion of bridge deck
  - both components of truss motion
- The profiles are used as boundary conditions for acoustic bridge model
- Linear interpolation between points

SPL Contours, Locomotive

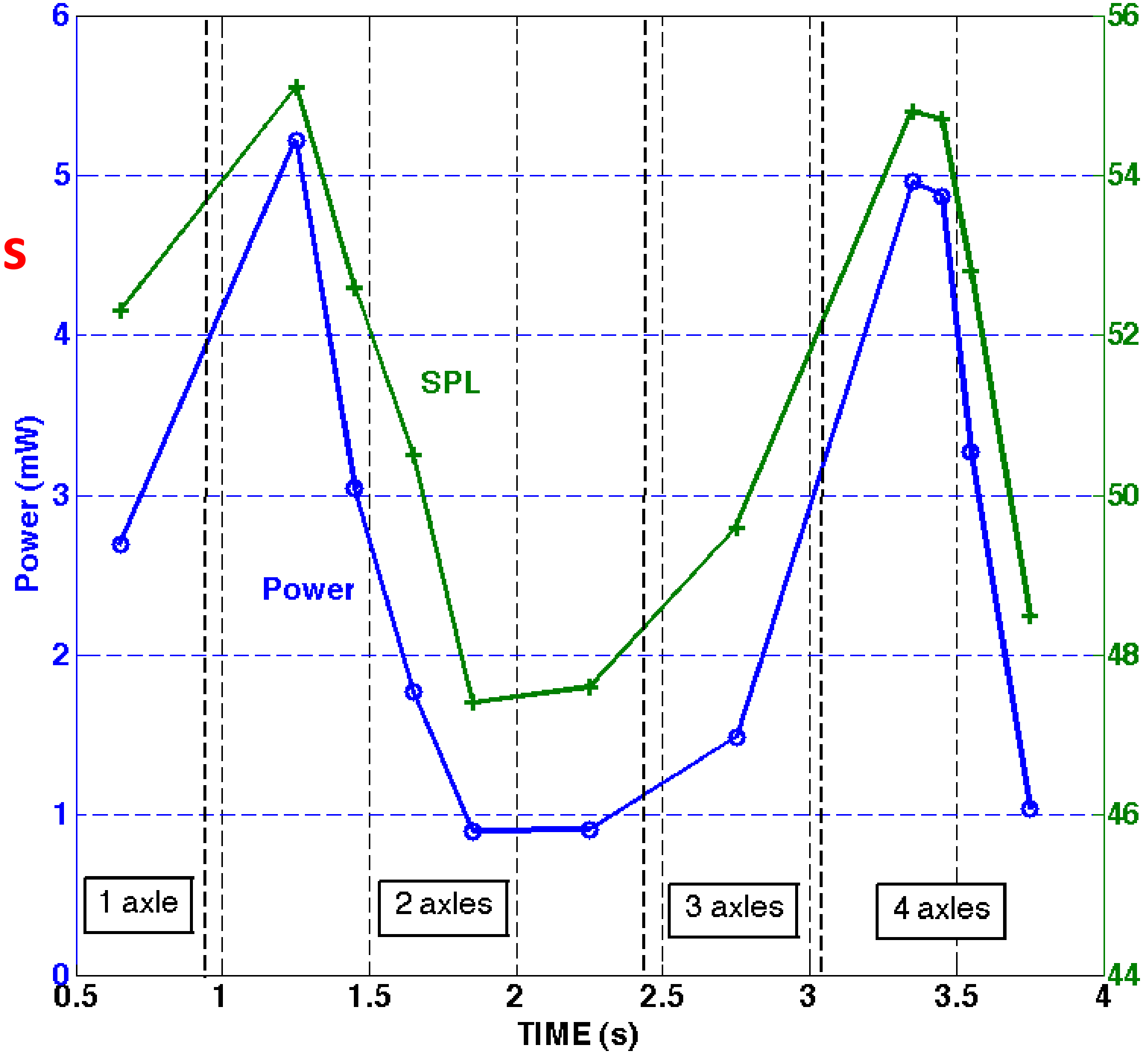
4.5 m/s; 8.5 Hz; 1-1.5 sec



Locomotive: Radiated Sound Power

SPL at Point 90 m directly above bridge deck

- **8.5 Hz Bin**
- **Successive 0.5 sec intervals**



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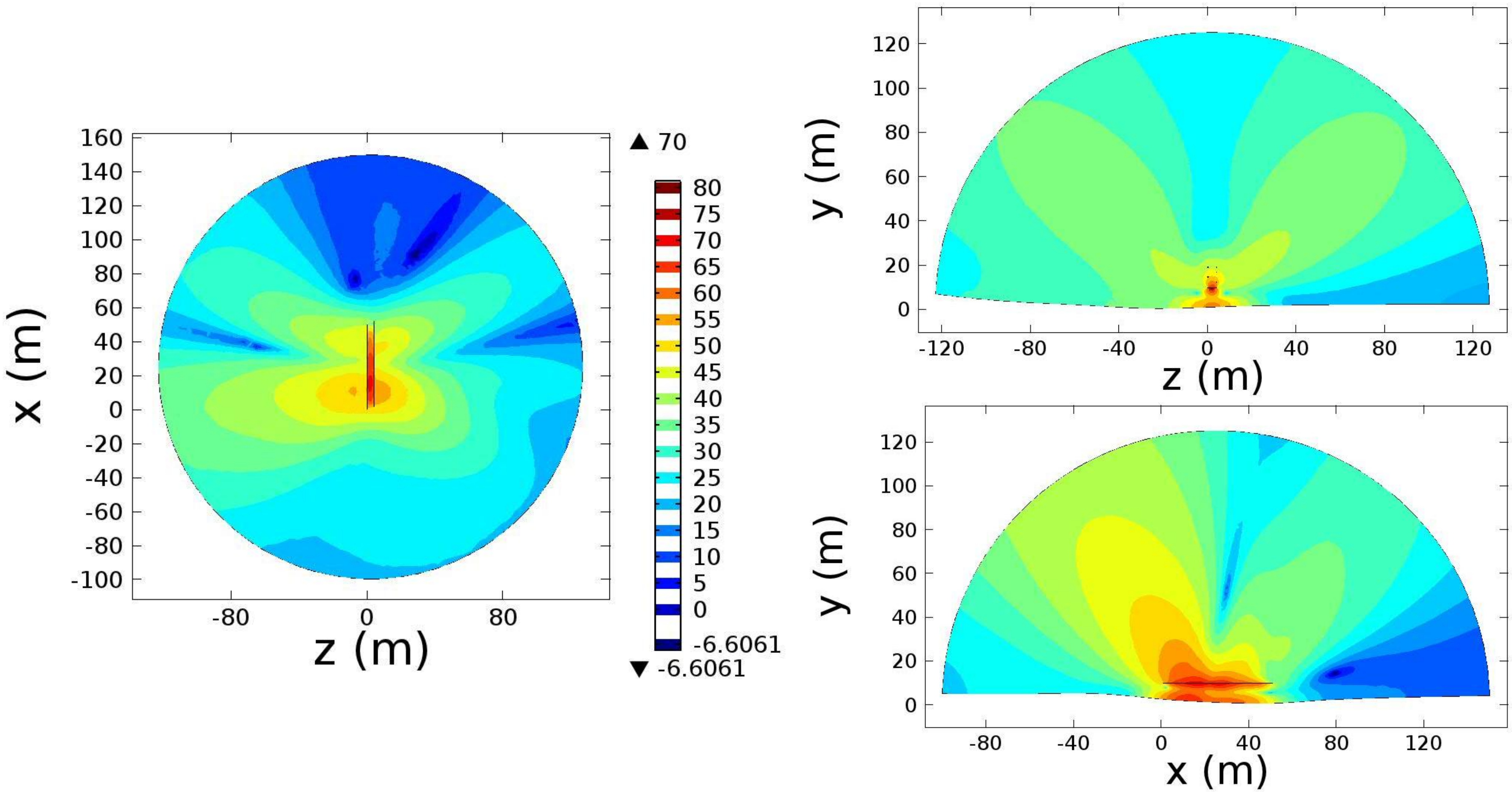
SPL Contours, Locomotive

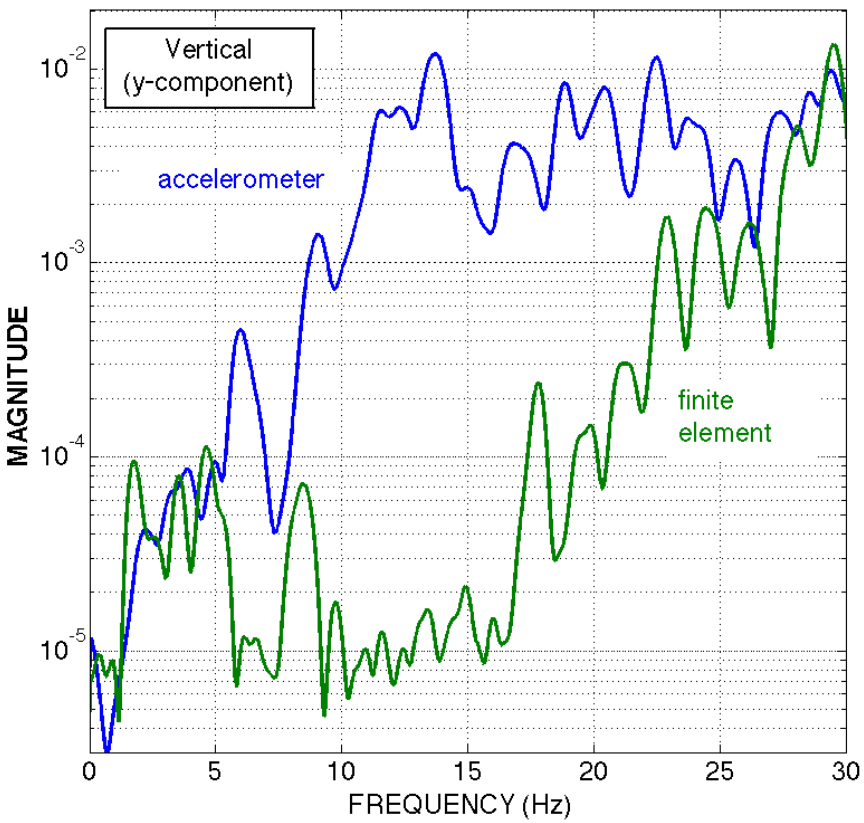
4.5 m/s; 18 Hz; 6-6.5 sec

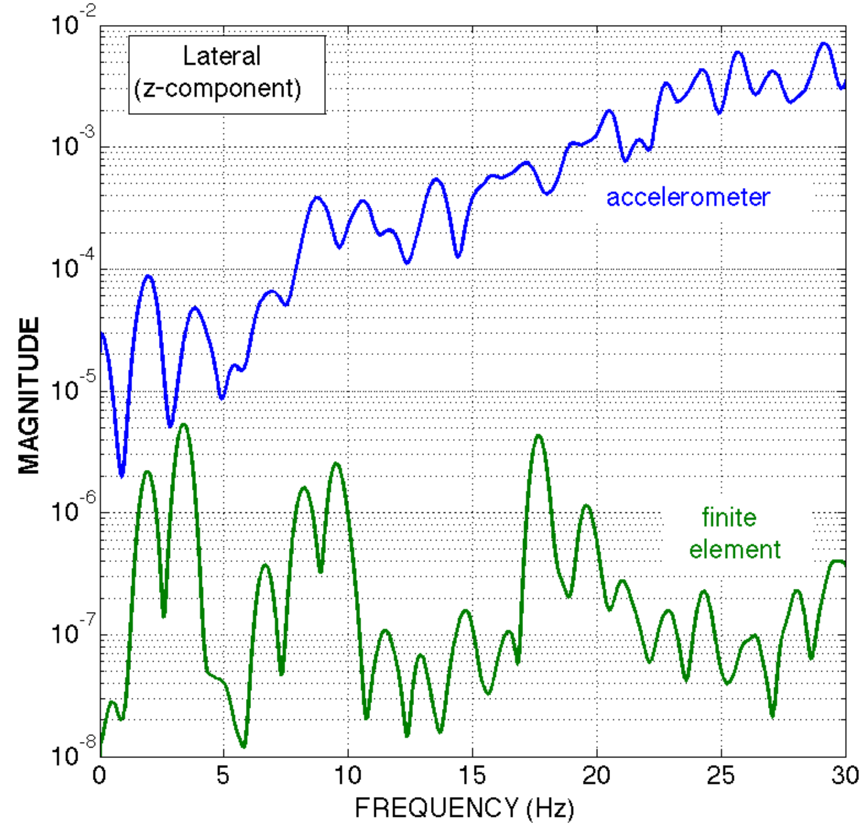


Summary & Conclusions

- Description of model
  - Euler Beam elements
  - Boundary Conditions
  - Representation of moving point load
- Structural model to determine motion of bridge deck & truss
  - Transient model
  - Single axle: simpler case for interpretation
  - Locomotive: more wheels crossing floor beams
  - Identified frequencies most likely to radiate detectable signals
- Acoustic response
  - Radiation pattern changes with frequency
  - Radiated power increases with:
    - axle weight
    - axle speed
    - number of axles
  - Vertical vibration of bridge deck - largest contributor to radiated sound
    - Largest accelerations, more surface area
    - Model does not consider porous nature of deck
    - Truss super-structure is smallest contributor
- Future efforts would include effects of vehicle suspension

FE Comparisons with Accelerometer Data

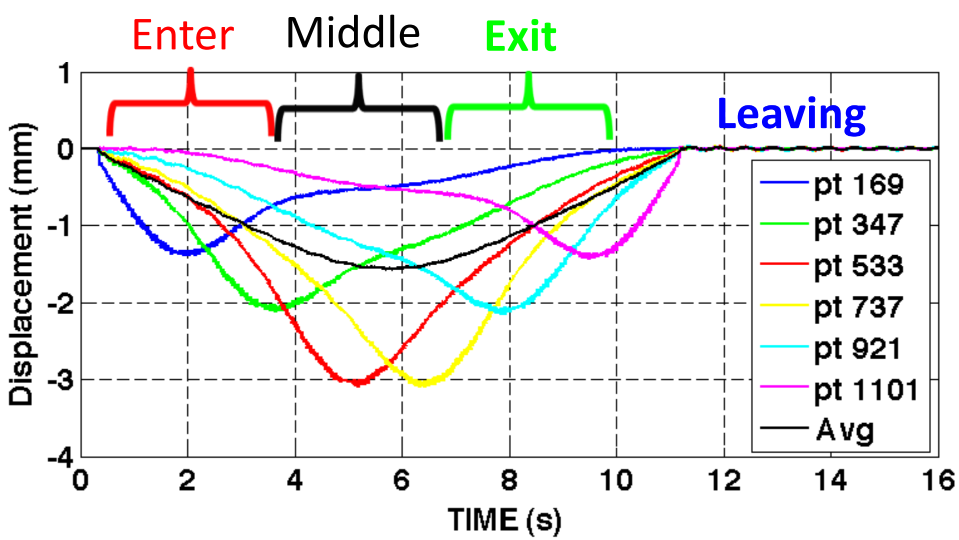


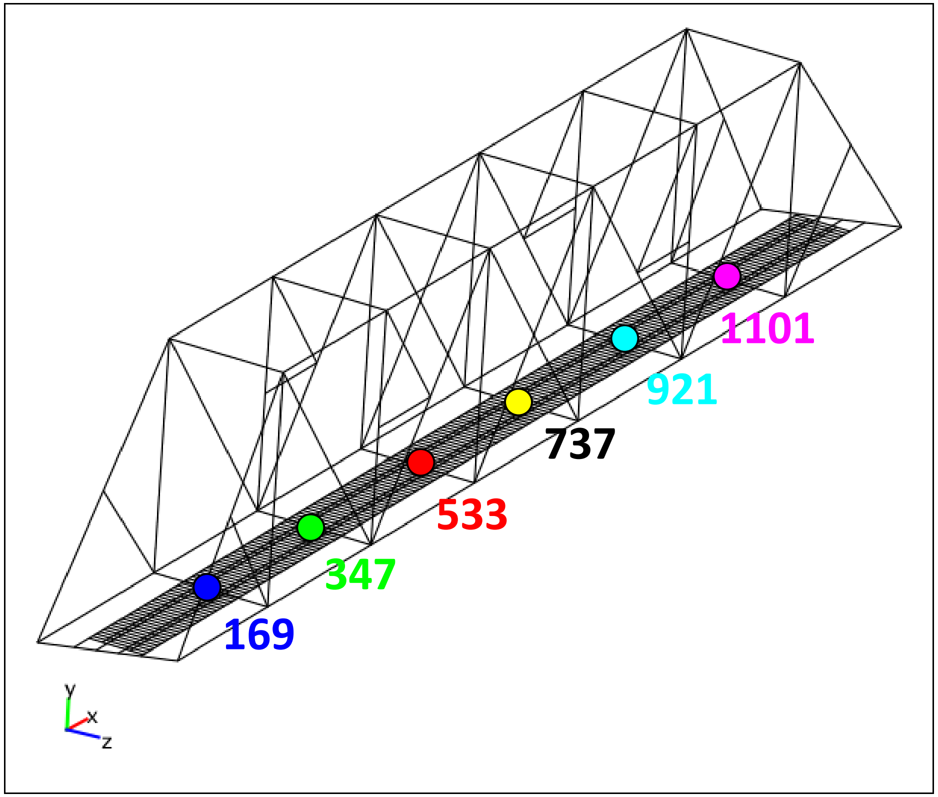


Average Vertical Motion of Bridge Deck

- Average displacement and acceleration represents bulk motion
  - Points that vibrate in-phase will add constructively
  - Function of frequency
- Bridge deck - larger surface area
  - Acoustic radiation

10 mph = 4.5 m/s

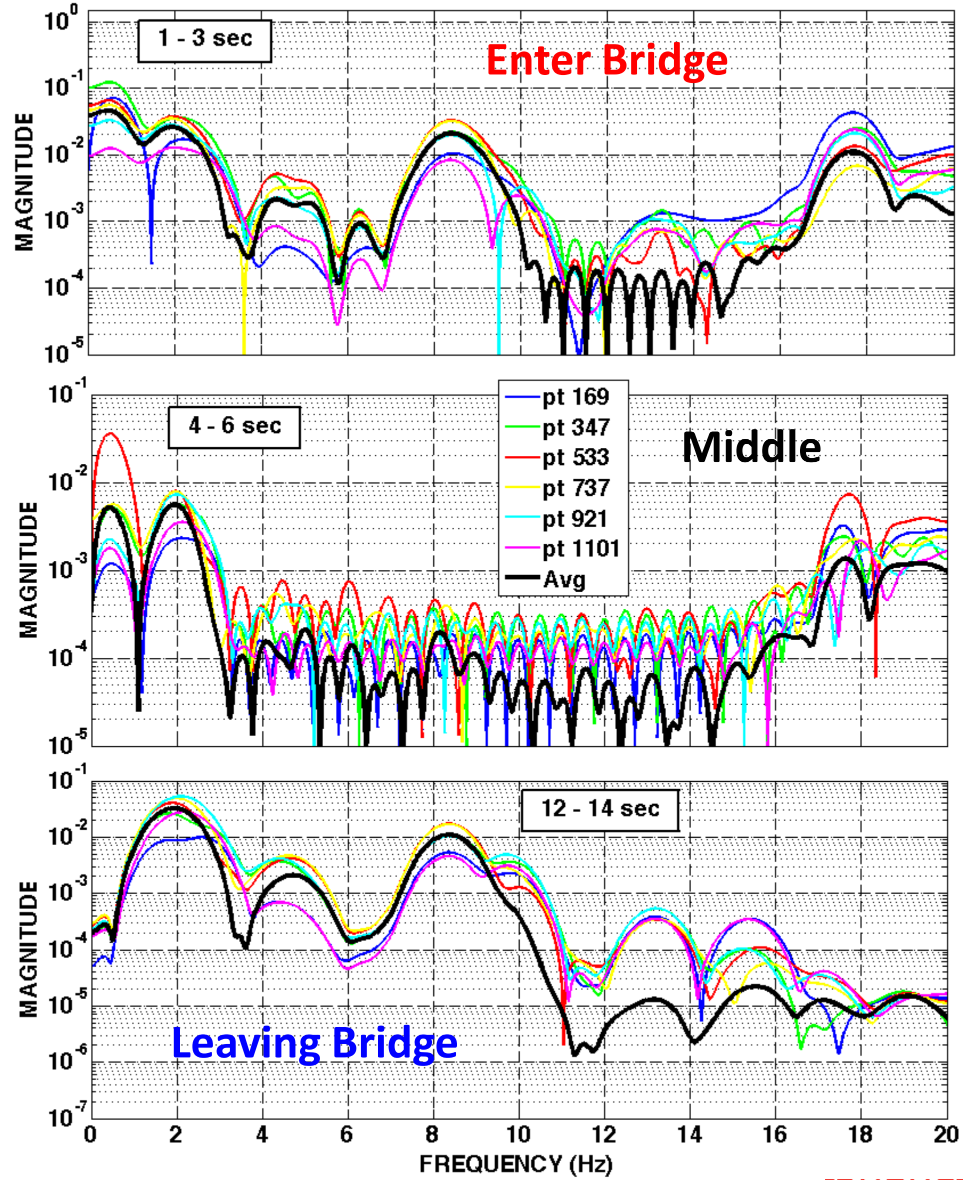




Frequency Spectra as Axle Crosses Bridge

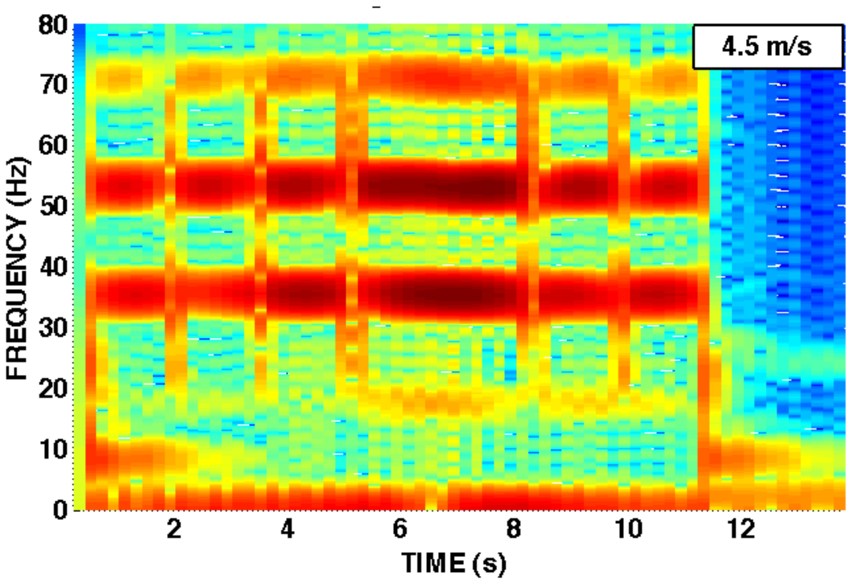
- **Enter**
  - Peaks at 2, 8, 18 Hz
- **Middle**
  - Peaks at 2 and 18 Hz
- **Leaving -** Natural frequencies
  - Peaks at 2 and 8, smaller peak at 5 Hz
  - Lost peak at 18 Hz
  - Peaks at 13 & 15 add destructively
- Large average responses indicate stringer is vibrating in phase at that frequency

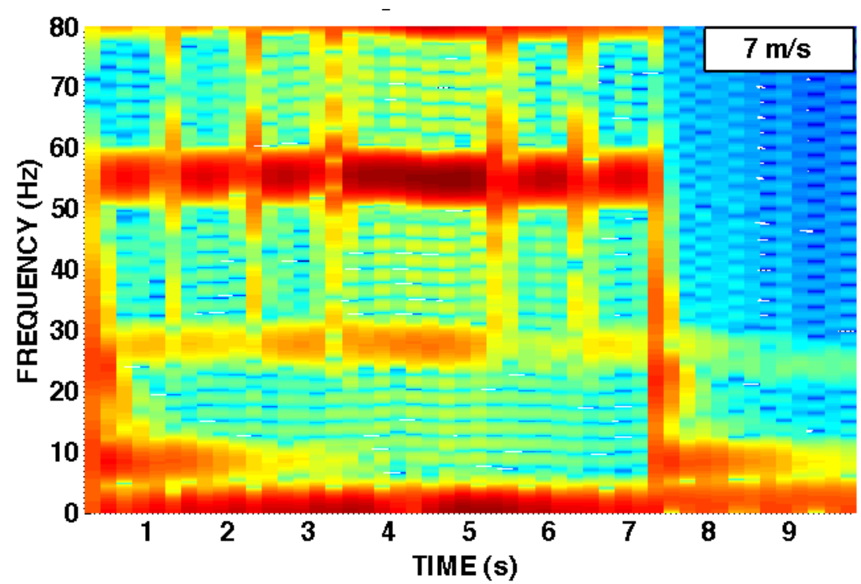
10 mph = 4.5 m/s

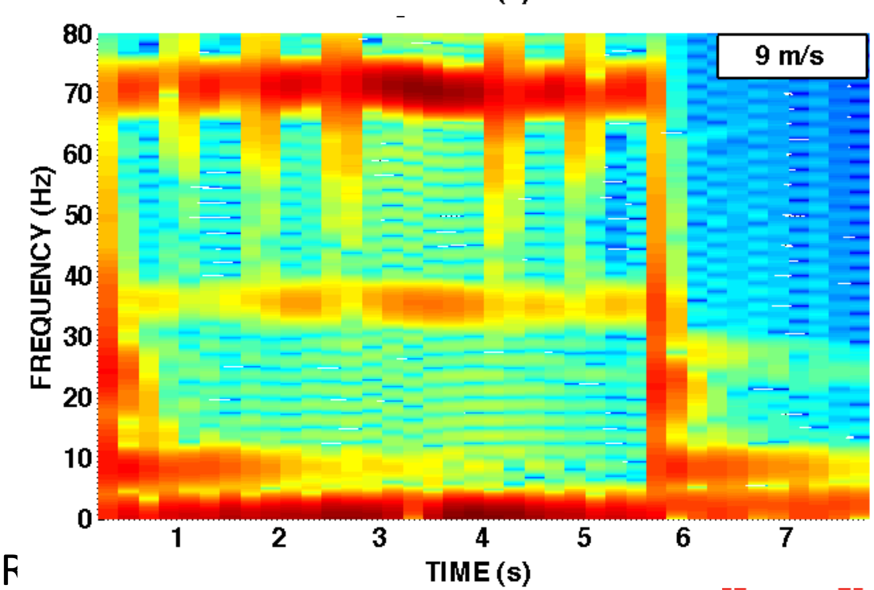


Effects of Changing Speed (single axle)

Sprectrograms from Particle Velocity near Center of Bridge







- Some frequencies bands change with speed:
  - 4.5 m/s: 18, 36, 54, 72 Hz
  - 7 m/s: 27, 54 Hz
  - 9 m/s: 36, 72 Hz
- Similarities:
  - 2 and 8 Hz vibration as axle enters and exits bridge

Case Studies

Radiated Power vs. speed and number of axles

Speed (m/s)	Frequency (Hz)	SPL (dB)	Power (mW)	Interval (sec)
Single Axle				
4.5	2	21.7	7.4e-3	11-12
7	2	24.3	1.3e-2	7-8
9	2	23.9	1.2e-2	5.5-6.5
4.5	8.5	52.8	3.0	0.4-0.9
7	8.5	53.0	3.3	0.3-0.8
9	8.5	53.8	3.7	0.2-0.7
4.5	18	22.6	9.2e-2	6-6.5
Locomotive				
4.5	2	28.1	3.2e-2	13-14
4.5	8.5	55.1	5.2	1-1.5
4.5	18	32.8	0.620	6-6.5

Case Studies

Radiated Power vs. axle weight

Axle Weight (kips)	Frequency (Hz)	SPL (dB)	Power (mW)	Window (sec)
20	2	11.5	6.96e-4	11-12
40	2	17.5	2.78e-3	11-12
65	2	21.7	7.4e-3	11-12
20	8.5	42.5	0.283	0.4-0.9
40	8.5	48.5	1.13	0.4-0.9
65	8.5	52.8	2.98	0.4-0.9
20	18	12.5	8.72e-3	6-6.5
40	18	18.5	3.49e-2	6-6.5
65	18	22.7	9.21e-2	6-6.5

SPL Contours, Locomotive

4.5 m/s; 2 Hz; 13-14 sec