Monitoring Bridge Vibrations via Pedestrians and Mobile Sensing

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NDT in Canada
NDTiC 2018
Canada's NDT Conference

June 19 - 21
Halifax Convention Centre
Halifax, Nova Scotia

- Introduction
- Biomechanical Models
- Walk-Induced Vibrations
- Transfer Functions
- Field Tests
- Results and Discussion
- Conclusion

Introduction

- Structural Health Monitoring (SHM)
- Mobile and Smart Sensors
- Smartphone-Based SHM
- SHM via Pedestrian Data
  - Stationary Form
  - Moving Form

Biomechanical Models

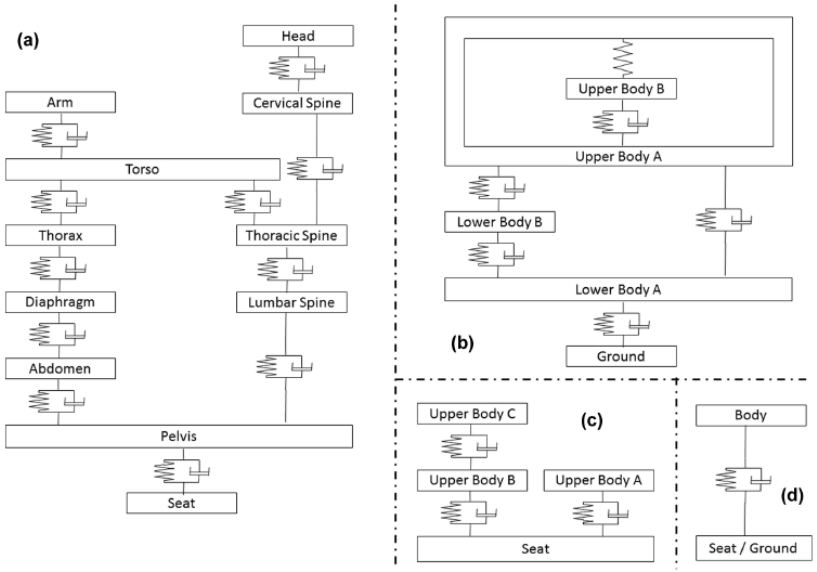
- Pedestrian Activity
  - Walking (Moving)
  - Standing (Stationary)

Mayagoitia RE, Nene AV and Veltink PH. Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis systems. *J Biomech* 2002; 35(4): 537–542.

Curone D, Bertolotti GM, Cristiani A, et al. A real-time and self-calibrating algorithm based on triaxial accelerometer signals for the detection of human posture and activity. *IEEE T Inf Technol B* 2010; 14(4): 1098–1105.

Wong WY, Wong MS and Lo KH. Clinical applications of sensors for human posture and movement analysis: a review. *Prosthet Orthot Int* 2007; 31(1): 62–75.

Qassem W, Othman MO and Abdul-Majeed S. The effects of vertical and horizontal vibrations on the human body. *Med Eng Phys* 1994; 16(2): 151–161.

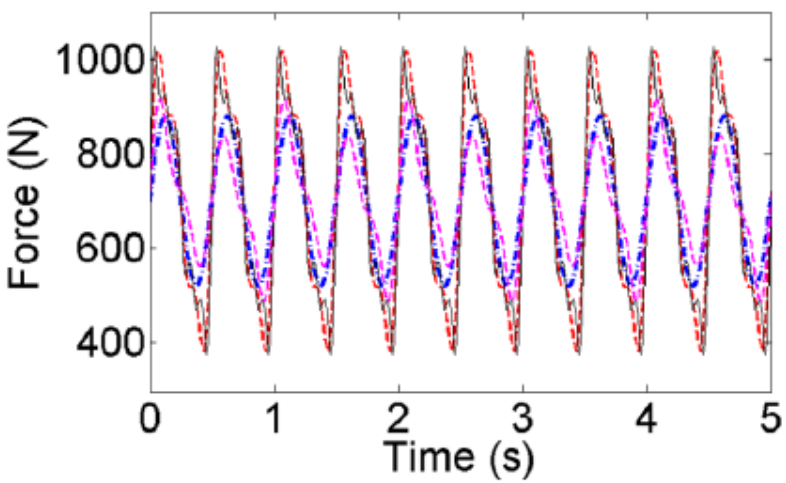


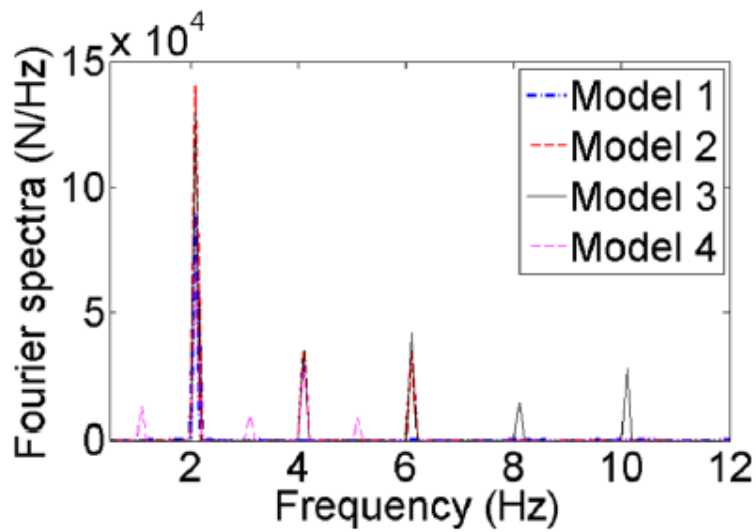
Walk-Induced Vibrations

- Theoretical Loads due to Pedestrian Motion

$$F_p(t) = G + \sum_{i=1}^{n} G \cdot \alpha_i \cdot \sin\left(2\pi i f_p t - \varphi_i\right)$$

Bachmann H and Ammann W. *Vibrations in structures: induced by man and machines*. Zürich: International Association for Bridge and Structural Engineering, 1987.





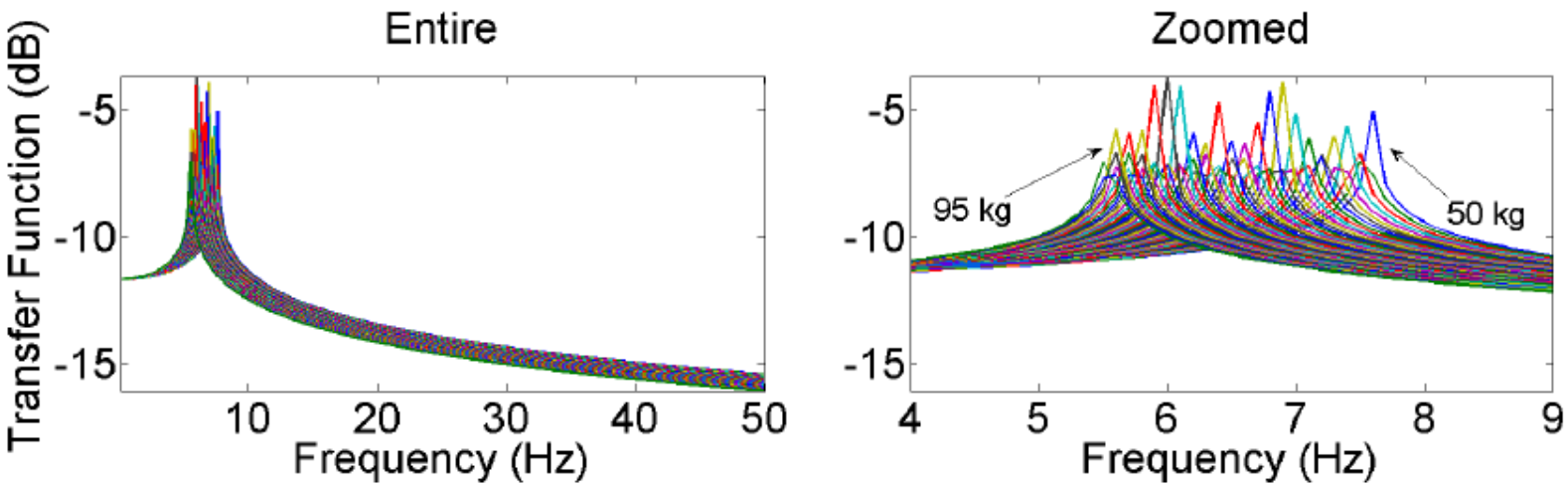
Transfer Functions

- Vibration Features of a Standing Pedestrian

$$H_{system}(w) = \frac{1}{\sqrt{(k - w^2 \cdot m)^2 + (w \cdot c)^2}}$$

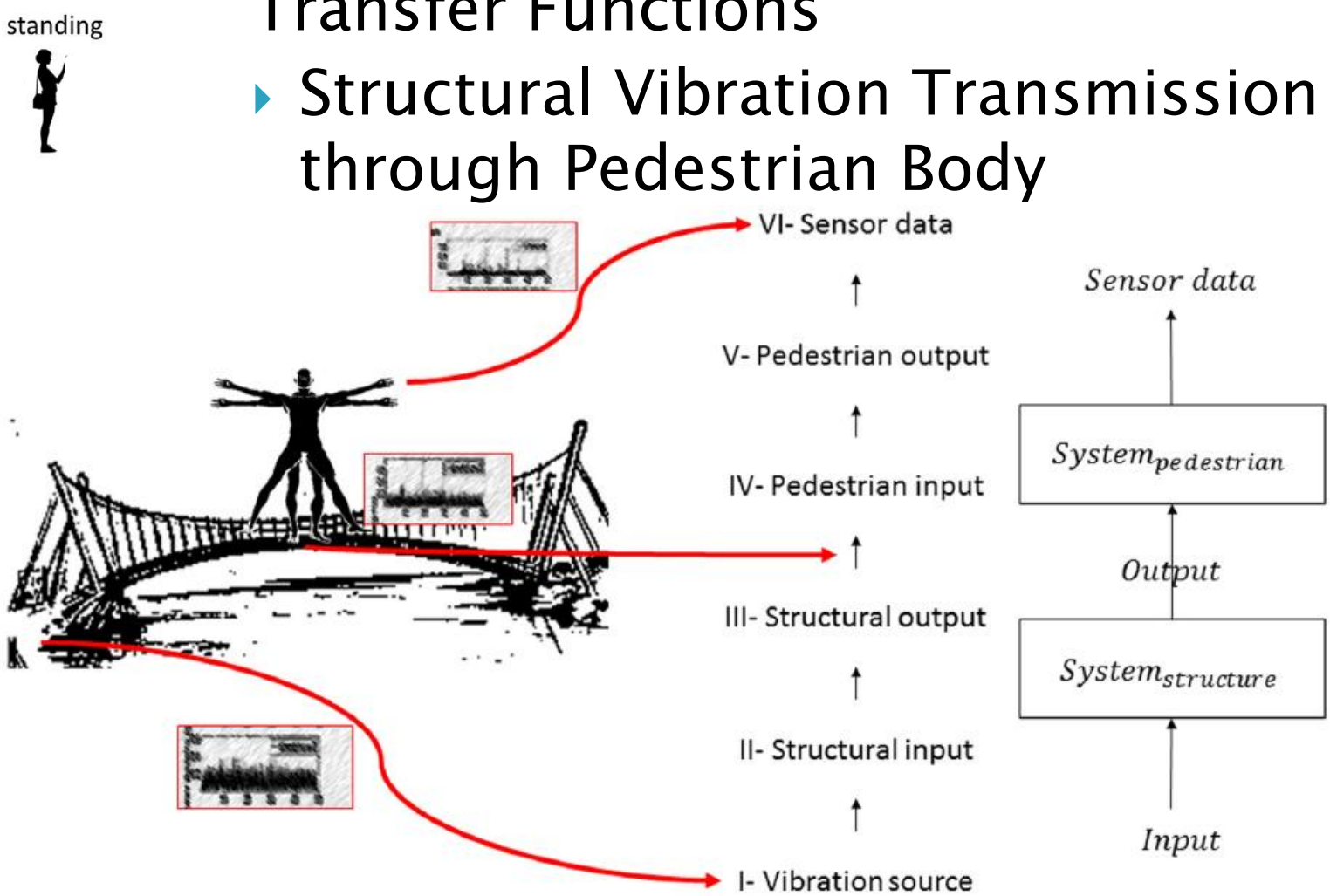
Ewins DJ. *Modal testing: theory, practice and application.* Baldock: Research Studies Press Ltd, 2000.

Inman DJ. *Engineering vibrations.* Upper Saddle River, NJ: Prentice Hall, 2000.



Transfer Functions

- Structural Vibration Transmission through Pedestrian Body



Transfer Functions

- Structural Vibration Transmission through Pedestrian Body

$$F_{output}(w) = H_{system}(w) \cdot F_{input}(w)$$

$$F_{intermediary}(w) = H_{structure}(w) \cdot F_{source}(w)$$

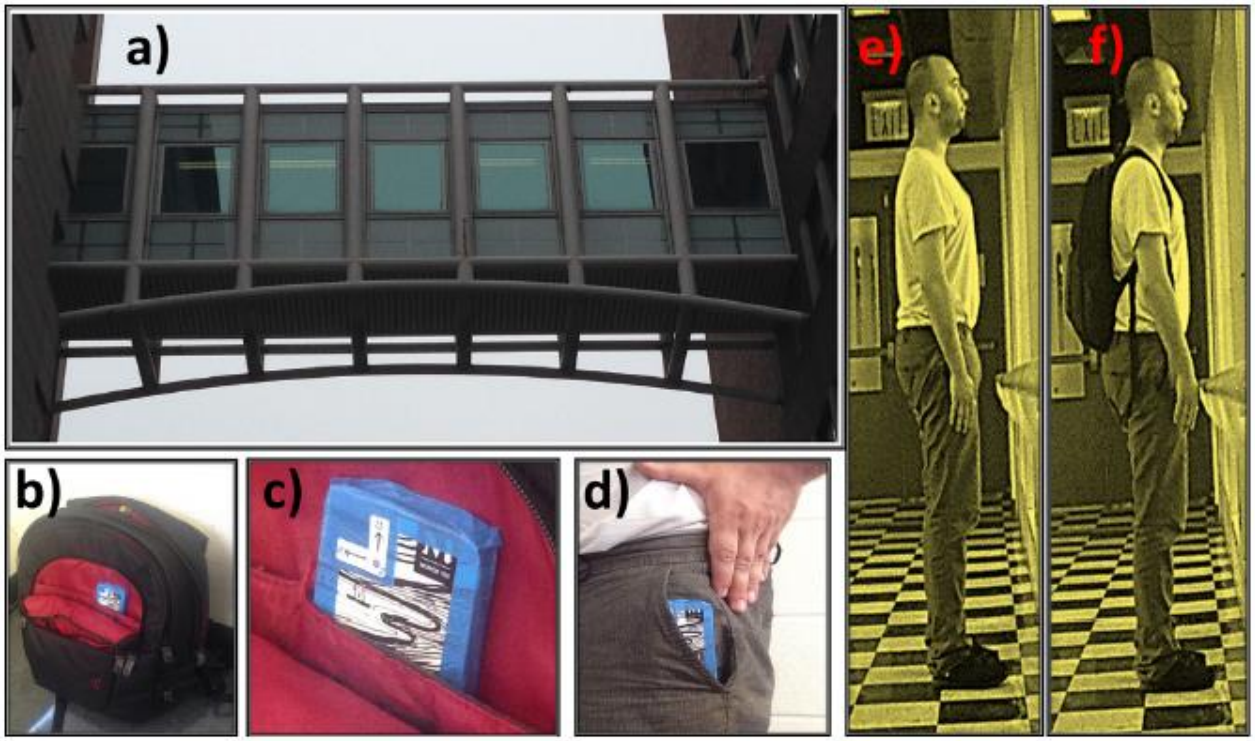
$$F_{sensor}(w) = H_{pedestrian}(w) \cdot F_{intermediary}(w)$$

$$H_{structure}(w) = \frac{F_{sensor}(w)}{H_{pedestrian}(w) \cdot F_{source}(w)}$$

$$H_{structure}(w) = \frac{F_{sensor}(w)}{H_{pedestrian}(w)}$$

Field Tests

- Pedestrian Bridge and Phone Location Scenarios



Field Tests

- Sources of Uncertainties

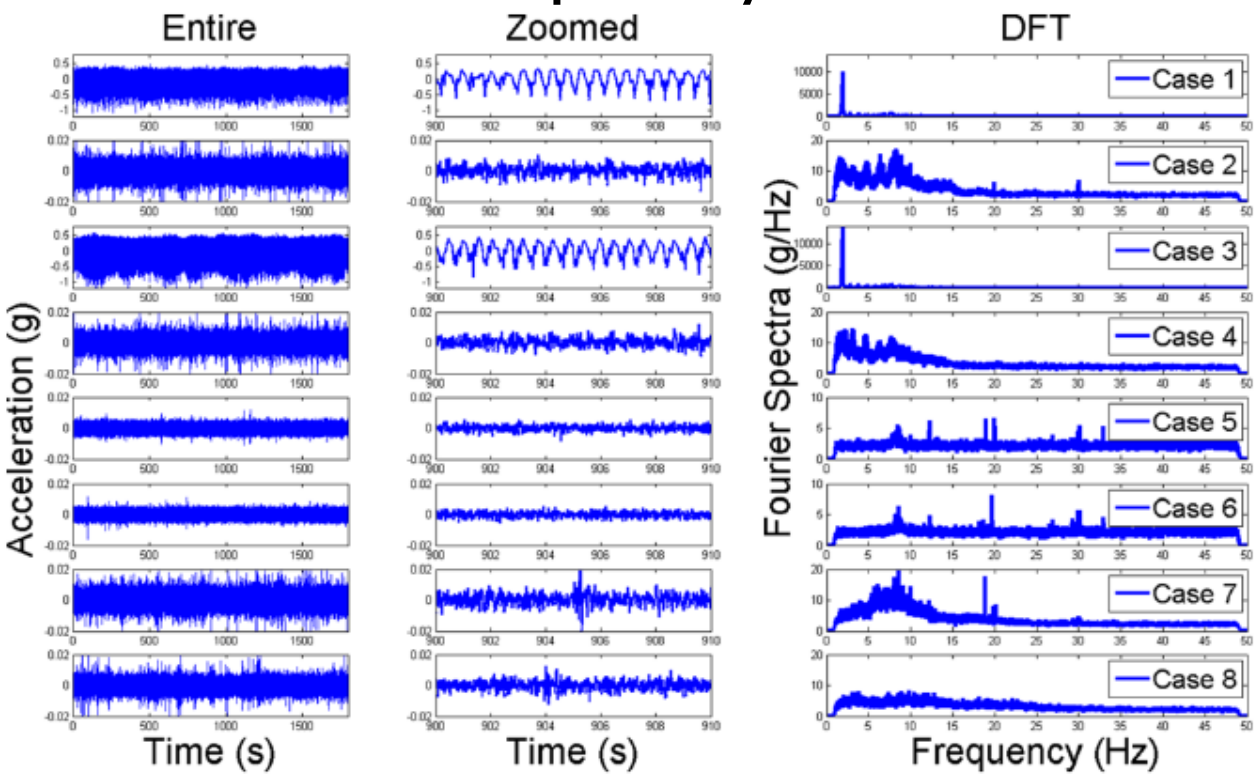
Source	Optimistic case	Pessimistic case	Affected process
Vibration	Ambient (broadband)	Operational (narrowband)	Loading
Activity	Stationary	Moving	Sensing/loading
Attachment	Direct (glued)	Indirect (e.g. pocket)	Sensing
Orientation	Face up or down/portrait/landscape	Combined	Sensing

- Test Descriptions

Case	Test	Location	Vibration	Device	Attachment	Orientation	Coupling	Measure
1	1–4	Bridge	Operational	Moving	Backpack and pedestrian	Portrait	Indirect	Output
2	5–8	Bridge	Ambient	Stationary	Backpack and pedestrian	Portrait	Indirect	Output
3	9–12	Street	Operational	Moving	Backpack and pedestrian	Portrait	Indirect	System
4	13–16	Street	Ambient	Stationary	Backpack and pedestrian	Portrait	Indirect	System
5	17–20	Bridge	Ambient	Stationary	Backpack on ground	Portrait	Semi-direct	Output
6	21–24	Bridge	Ambient	Stationary	Phone on ground	Portrait	Direct	Output
7	25–28	Bridge	Ambient	Stationary	Pocket and pedestrian	Portrait	Indirect	Output
8	29–32	Street	Ambient	Stationary	Pocket and pedestrian	Portrait	Indirect	System

Field Tests

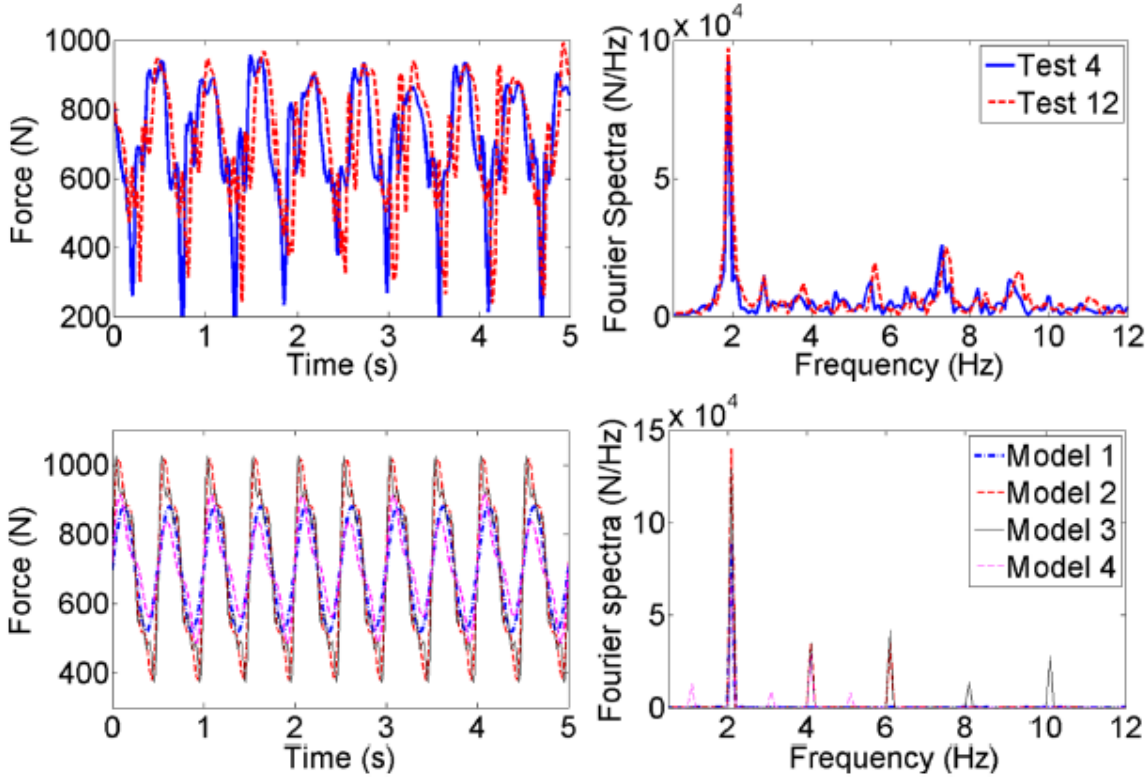
- Pedestrian Measurements in Time and Frequency Domain



(a) (b)

Results and Discussion

- Walk-Induced Forces Identified by the Smartphone



Results and Discussion

- Isolating Biomechanical Effects from Standing Pedestrian Data

Bridge (Case 2, 7)

$$H_{smartphone} = f(H_{pedestrian}, H_{bridge})$$

A combination of pedestrian biomechanics and structural system:

Transfer function measured by the smartphone in citizen's pocket/bag is

$$\frac{H_{output*}}{H_{system*}} = H_{input*} = H_{output**}$$

Only a function of pedestrian biomechanical system:

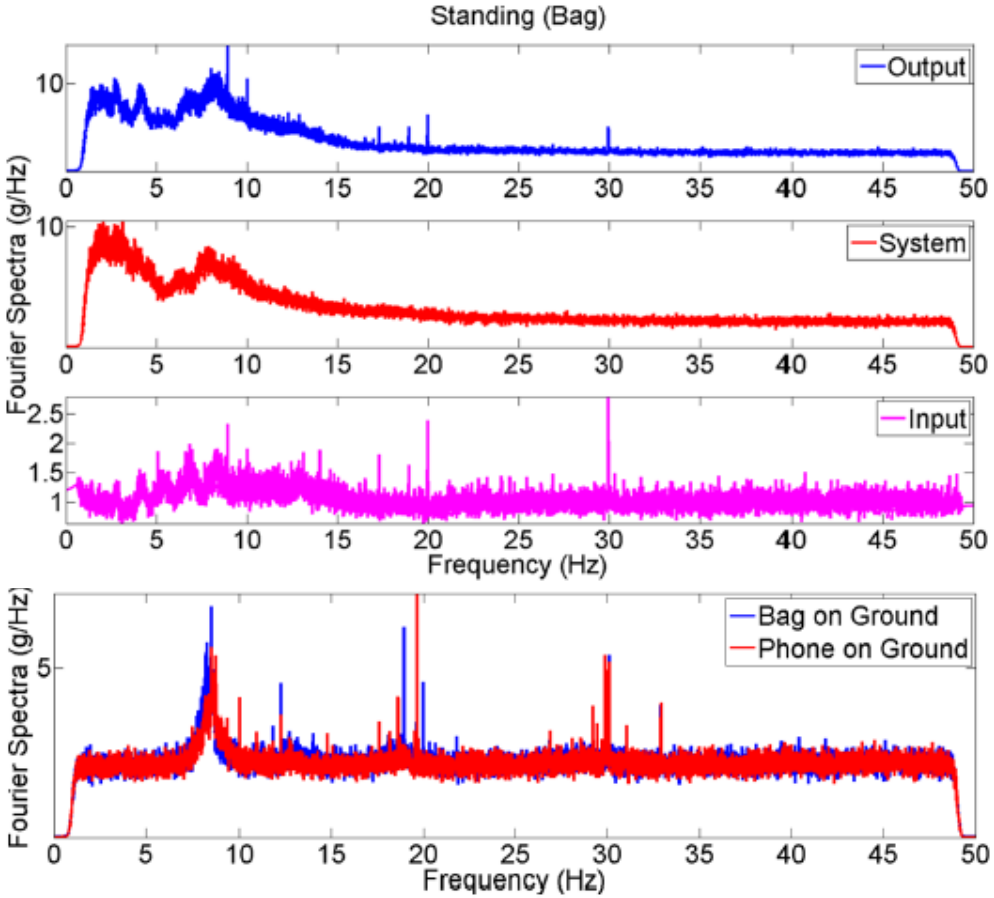
Rigid Zone (Case 4, 8)

$$H_{smartphone} = f(H_{pedestrian})$$

$** \; structure$

$* \; pedestrian$

- Results and Discussion
- Biomechanical Effect Isolation



This presentation is adapted from:

- **Ozer, E.,** & Feng, M. Q. (2017). Biomechanically Influenced Mobile and Participatory Pedestrian Data for Bridge Monitoring. *International Journal of Distributed Sensor Networks, 13*(4), 1550147717705240.

Relevant References

- Feng, M., Fukuda, Y., Mizuta, M., & **Ozer, E.** (2015). Citizen Sensors for SHM: Use of Accelerometer Data from Smartphones. *Sensors*, *15*(2), 2980–2998.
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- **Ozer, E.,** & Feng, M. Q. (2016). Synthesizing Spatiotemporally Sparse Smartphone Sensor Data for Bridge Modal Identification. *Smart Materials and Structures, 25*(8), 085007.
- **Ozer, E.,** & Feng, M. Q. (2017). Direction-Sensitive Smart Monitoring of Structures Using Heterogeneous Smartphone Sensor Data and Coordinate System Transformation. *Smart Materials and Structures, 26*(4), 045026.

- Thank You.