Realizing a Self-powered Real-time Monitoring System on High-speed Trains

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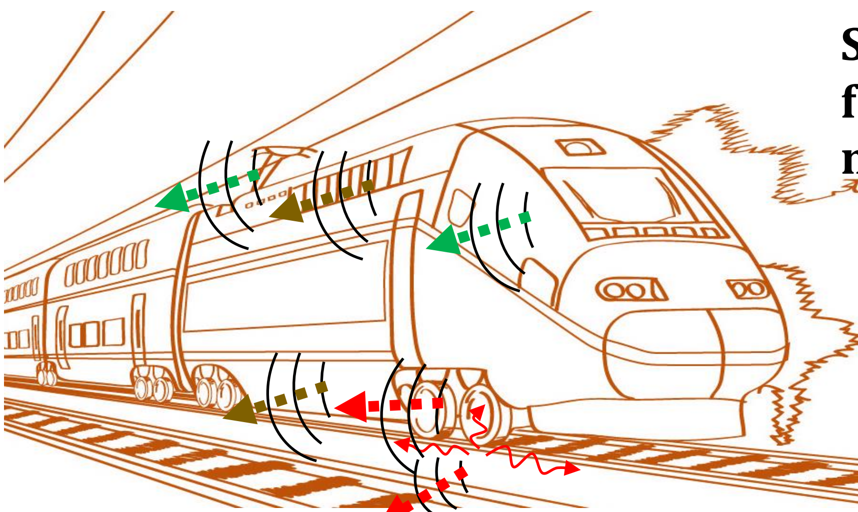
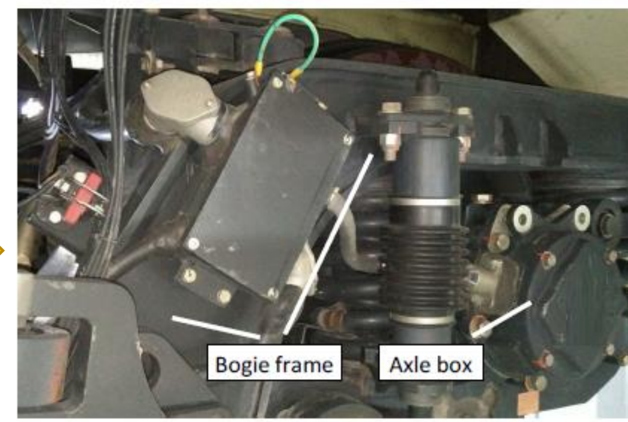
Research Motivation

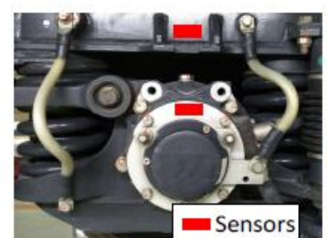
- Vibration-induced responses between wheel-rail interactions due to rail irregularity (smoothness), short-pitch corrugation, or wheel defect (polygonization) etc.
- There are many sensors deployed on train bogies for monitoring the ride comfort and safety.
- Power supply for the sensors is still a problem!

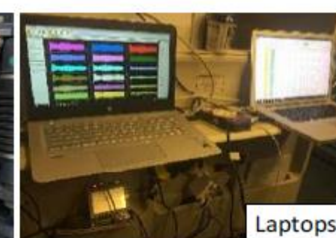
Rail corrugation



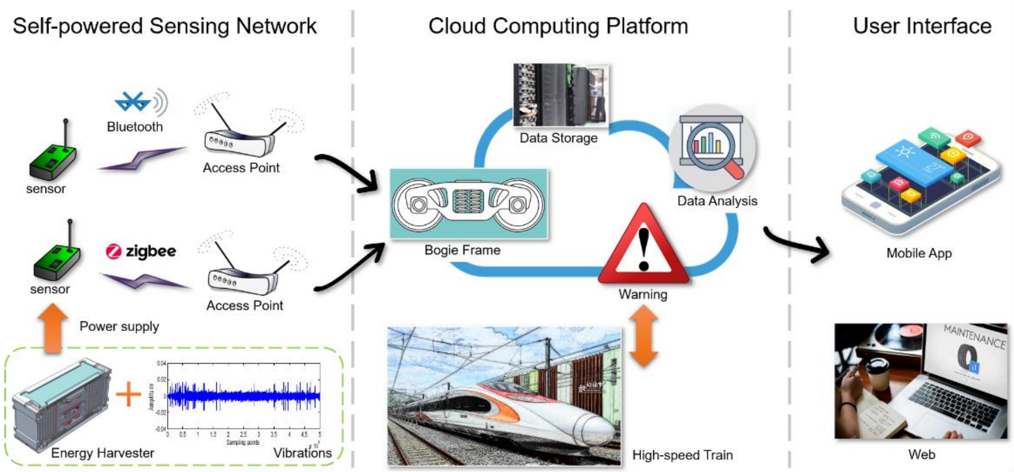
Sensors on bogie for health monitoring



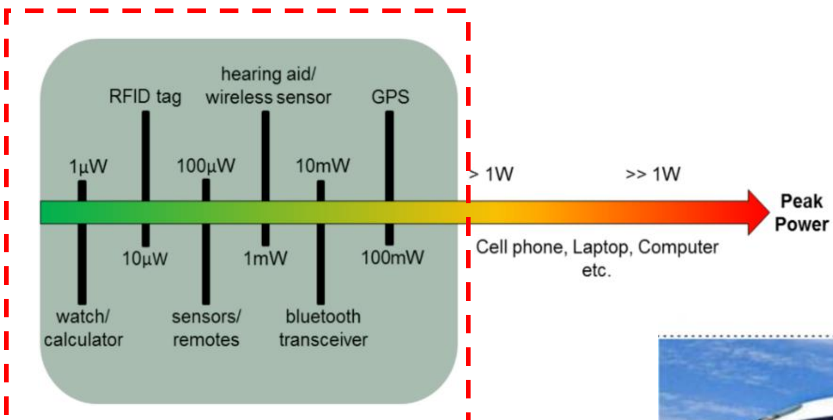




Key Issues



A self-powered real-time monitoring system for high-speed trains



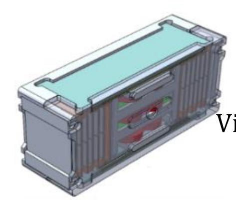
Power scales of various electronics

For high-speed/metro trains, vibrations of the bogie frames are generally:

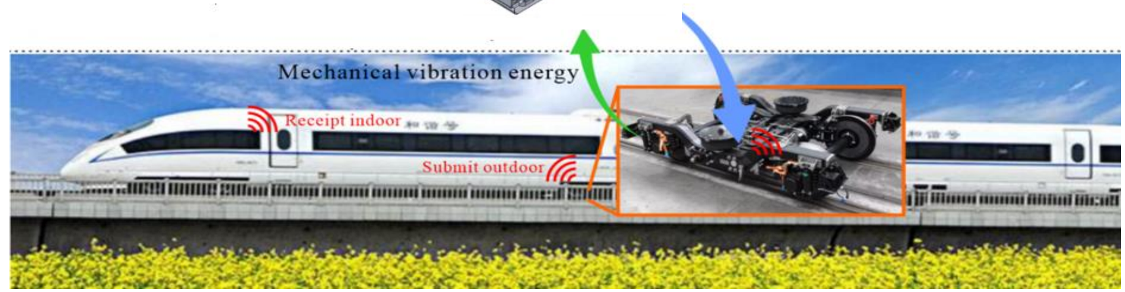
- low-frequency (≈ 8–40 Hz)
- low-amplitude (≈ 0.5–2 g*)
- time-varying
- speed-dependent

(*1 g = 9.8 m/s^2)

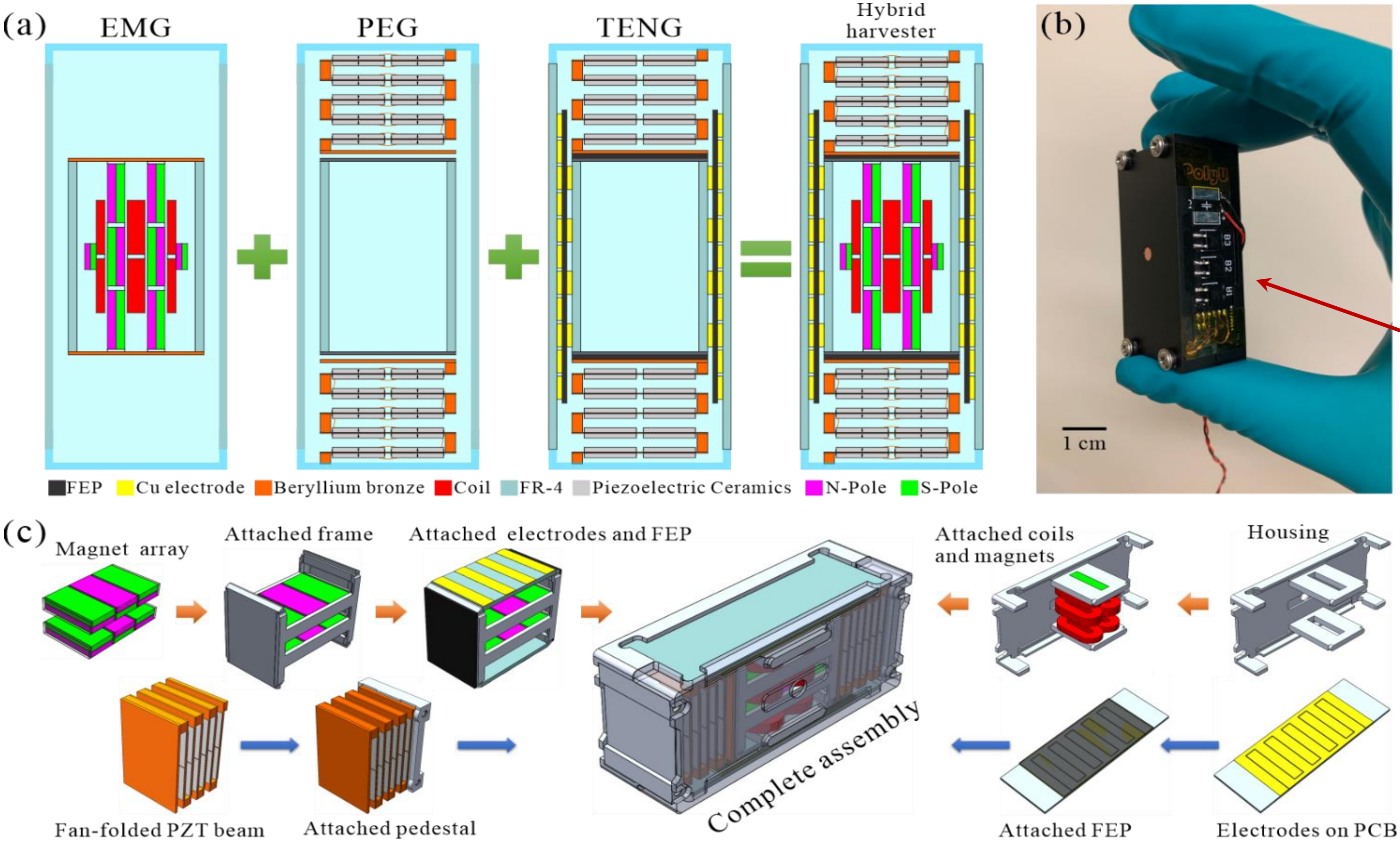
Present Work:
For monitoring wheel defects and abnormal vibrations, we aim to develop a **high efficient vibration-based tri-hybrid energy harvesting technique**, which can power up wireless sensor networks for real-time monitoring of the bogie frame and suspension system of high-speed/metro trains.



Vibration-based tri-hybrid energy harvester deployed on train bogies



Fabrication of Tri-hybrid Energy Harvester*

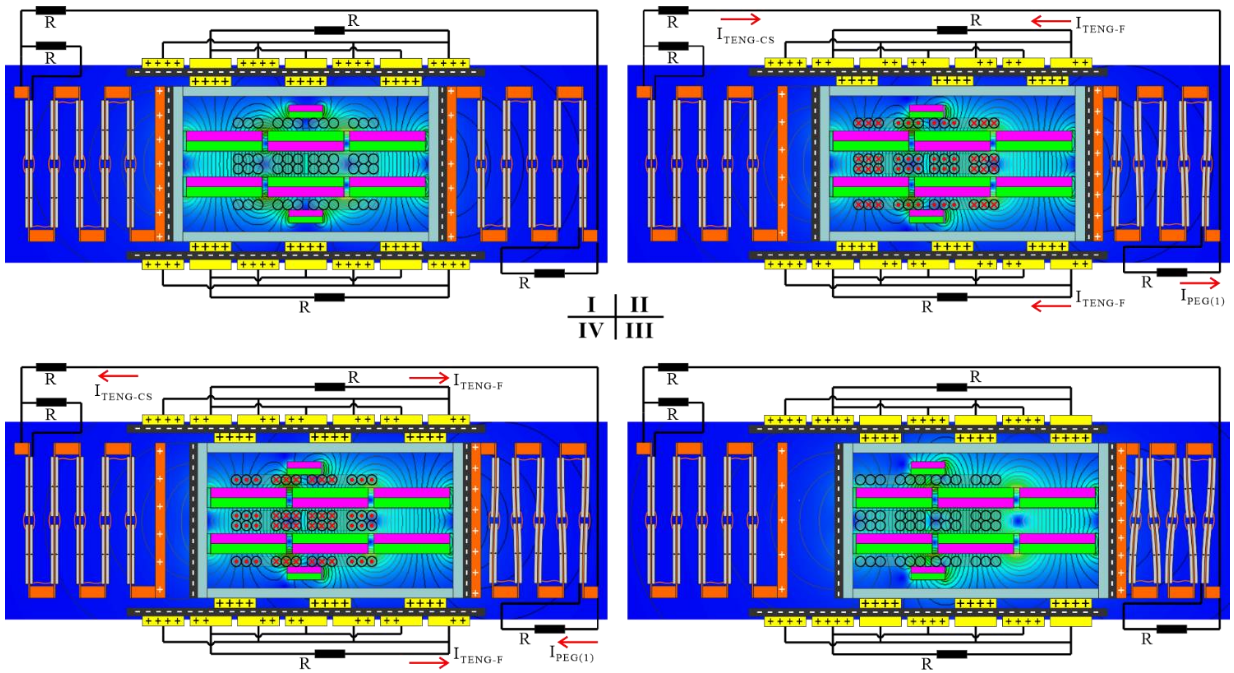


Dimensions:
70 × 25 × 18 mm^3

EMG: Electromagnetic generator; **PEG**: Piezoelectric generator; **TENG**: Triboelectric generator

C. Wang, S.K. Lai, J.M. Wang, J.J. Feng and Y.Q. Ni, *Applied Energy*, Vol. 291, 116825, 2021.

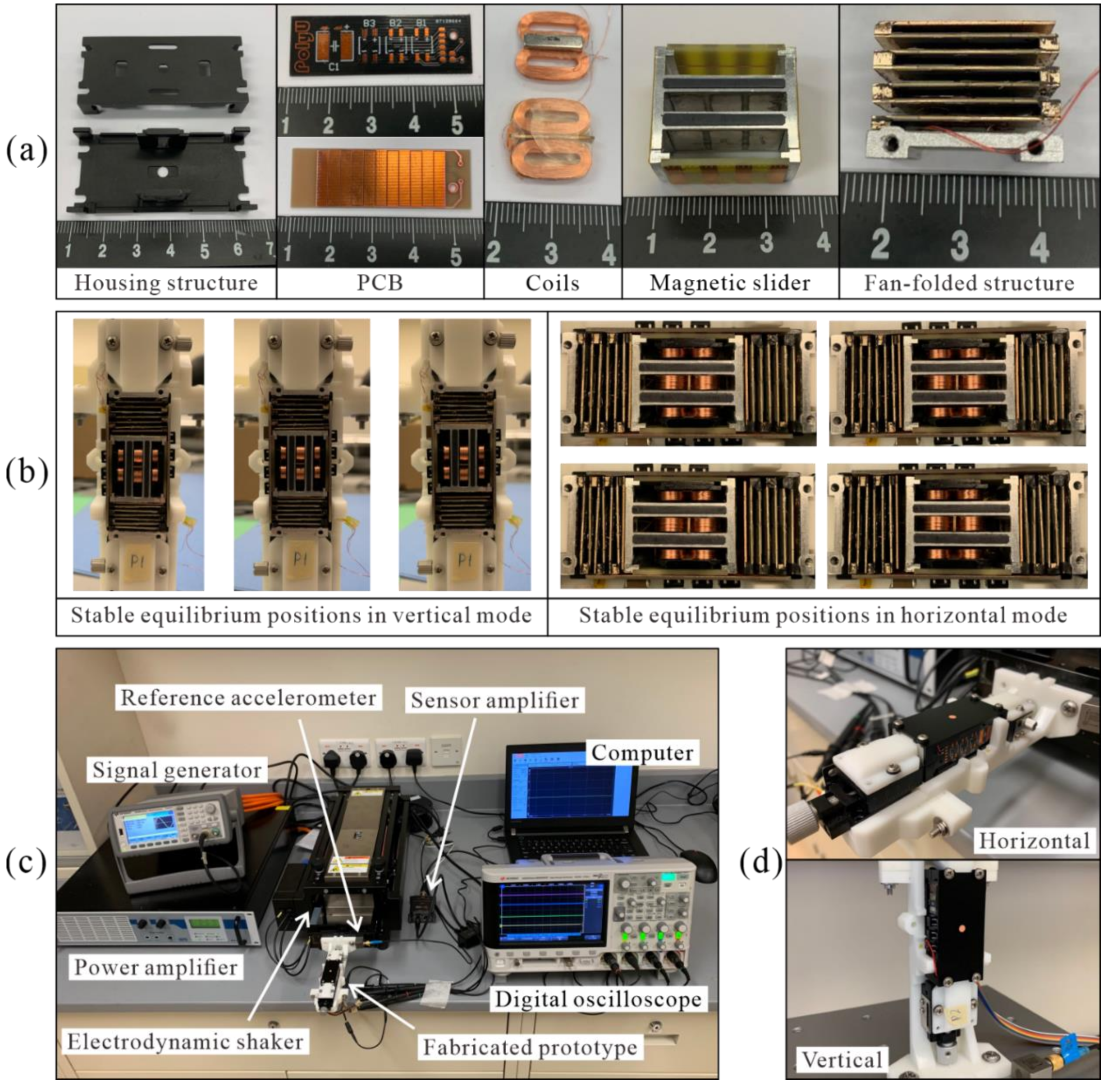
*Tri-hybrid Energy Harvester**

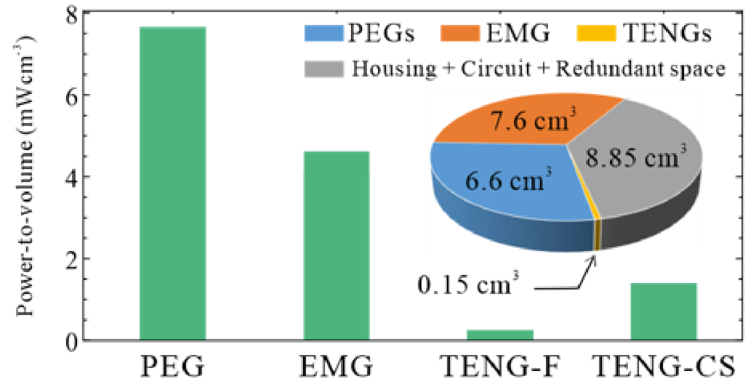


- The standardized power density of our new prototype is **3.70 mW/cm^3/g^2 (under 1 g)**.
- The prototype works well at a wide bandwidth of **1–11 Hz** under 1 g (= 9.8 m s^{-2}).
- It can generate a maximum output power of **86 mW**.
- Under an excitation (8 Hz and 1 g), our new **tri-hybrid energy harvester** (for **1 cm^3** volume size) can actuate a sensor network of 400 mW for 12.9 s within a 30-min period, ignoring the energy loss of storage process.

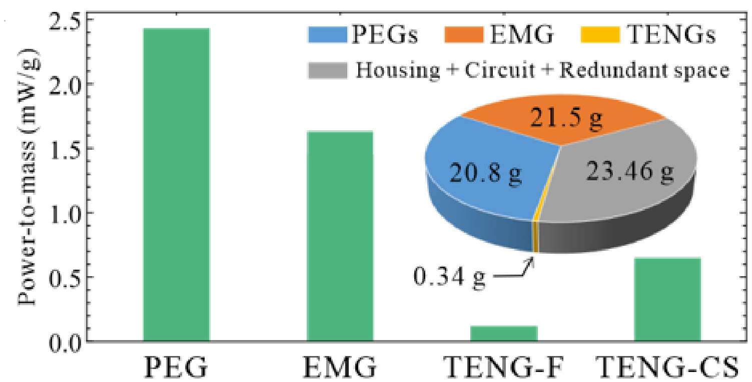
C. Wang, S.K. Lai, J.M. Wang, J.J. Feng and Y.Q. Ni, *Applied Energy*, Vol. 291, 116825, 2021.

Shaker test results



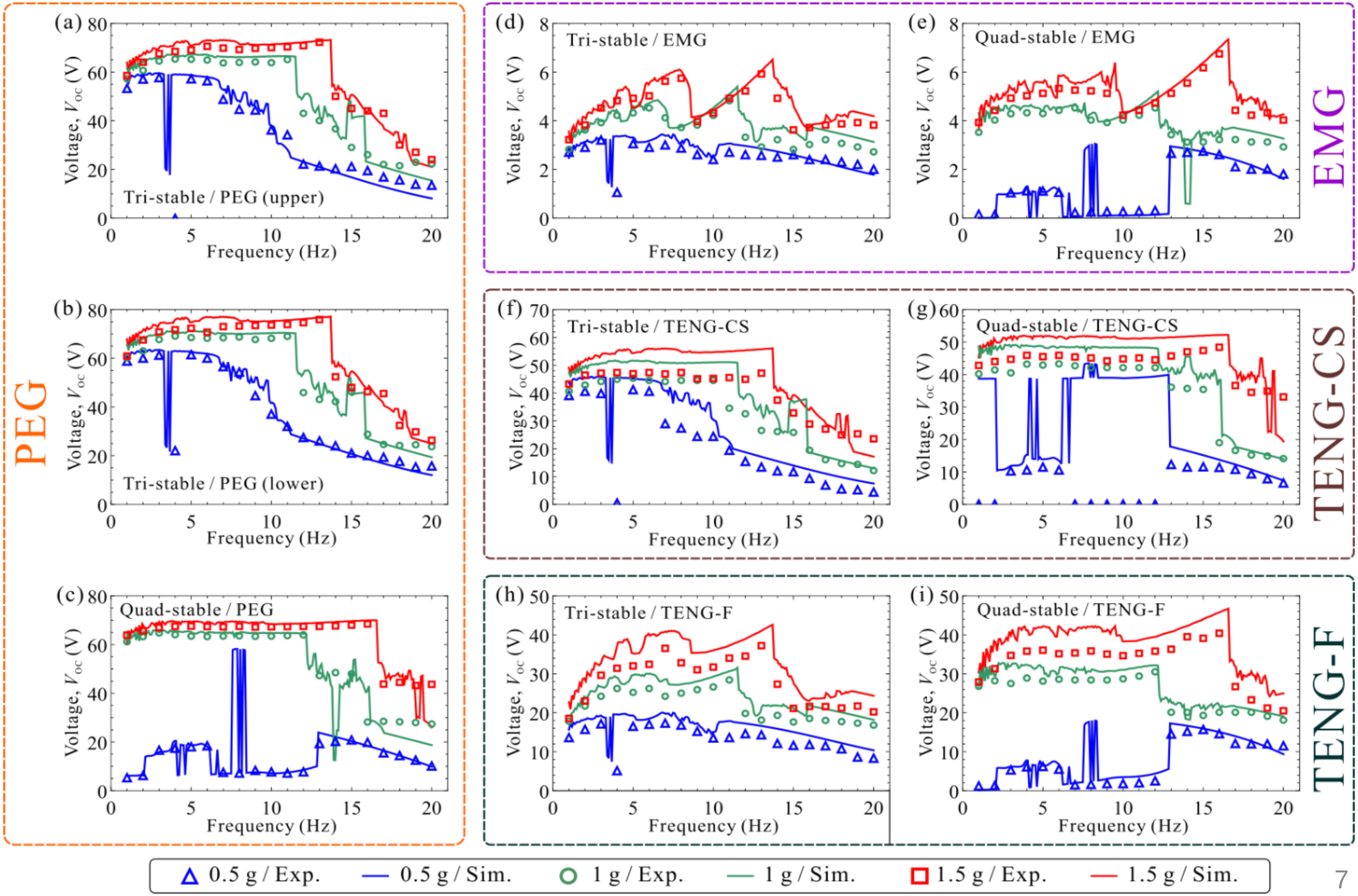


Power-to-volume ratios of the PEG, EMG and TENG units under 1g and 3 Hz

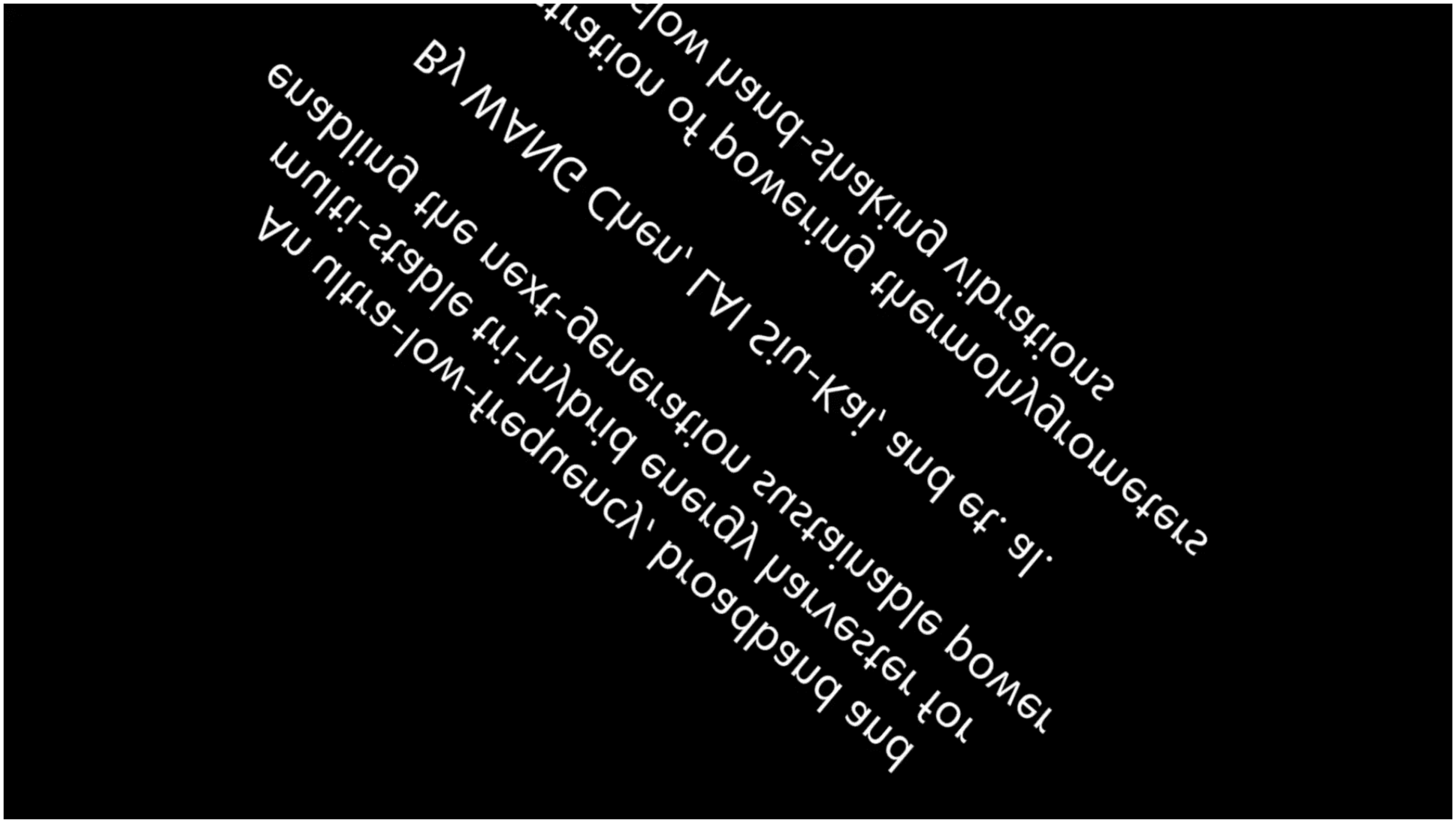


Power-to-mass ratios of the PEG, EMG and TENG units under 1g and 3 Hz

Shaker test results



Application to electronic devices
(Power up 20 electronic meters by low-frequency motions)

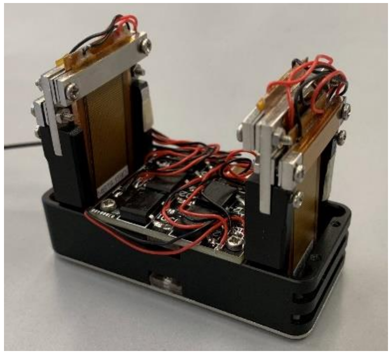


Performance comparison

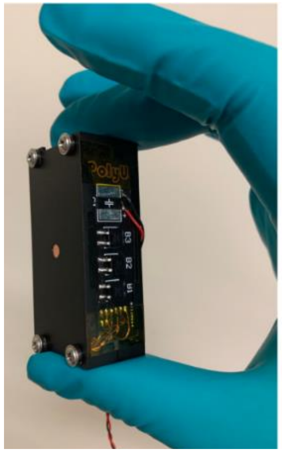
Table 1. Comparison of the proposed new energy harvester with other works reported recently.

Reference (Types), Year	**Bandwidth (Hz)**	**Normalized Power Density**
Ref. [1] (EM+TE), 2020	3.5–7 Hz, 1g	3.67 mW cm^{-3} g^{-2}, 5 Hz
Ref. [2] (PE+EM+TE), 2018	10–31.5 Hz, 0.5 g	2.16×10^{-2} mW cm^{-3} g^{-2}
Ref. [3] (PE+EM+TE), 2019	2–5 Hz, 1 g	3.2 mW cm^{-3}, 5 Hz
Ref. [4] (EM+TE), 2020	4–9 Hz, 1 g	3.15 mW cm^{-3} g^{-2}, 6 Hz
Our Original Design [5] (PE+EM+TE), 2019	2–12.5 Hz, 1 g	1.97 mW cm^{-3} g^{-2}, 5 Hz
Our New Design [6] (PE+EM+TE), 2021	1–11 Hz, 1 g	3.70 mW cm^{-3} g^{-2}, 3 Hz

References:
[1] R.M. Toyabur et al., Applied Energy 279 (2020) 115799.
[2] J. He et al., Nano Energy 43 (2018) 326–339.
[3] P.C. Tan et al., Advanced Energy Materials 9 (2019) 1901875.
[4] M.T. Rahman et al., Advanced Energy Materials 10 (2020) 1903663.
[5] C. Wang et al., Nano Energy 64 (2019) 103943.
[6] C. Wang et al., Applied Energy 291 (2021) 116825.



Our Original Design in 2019 [5]



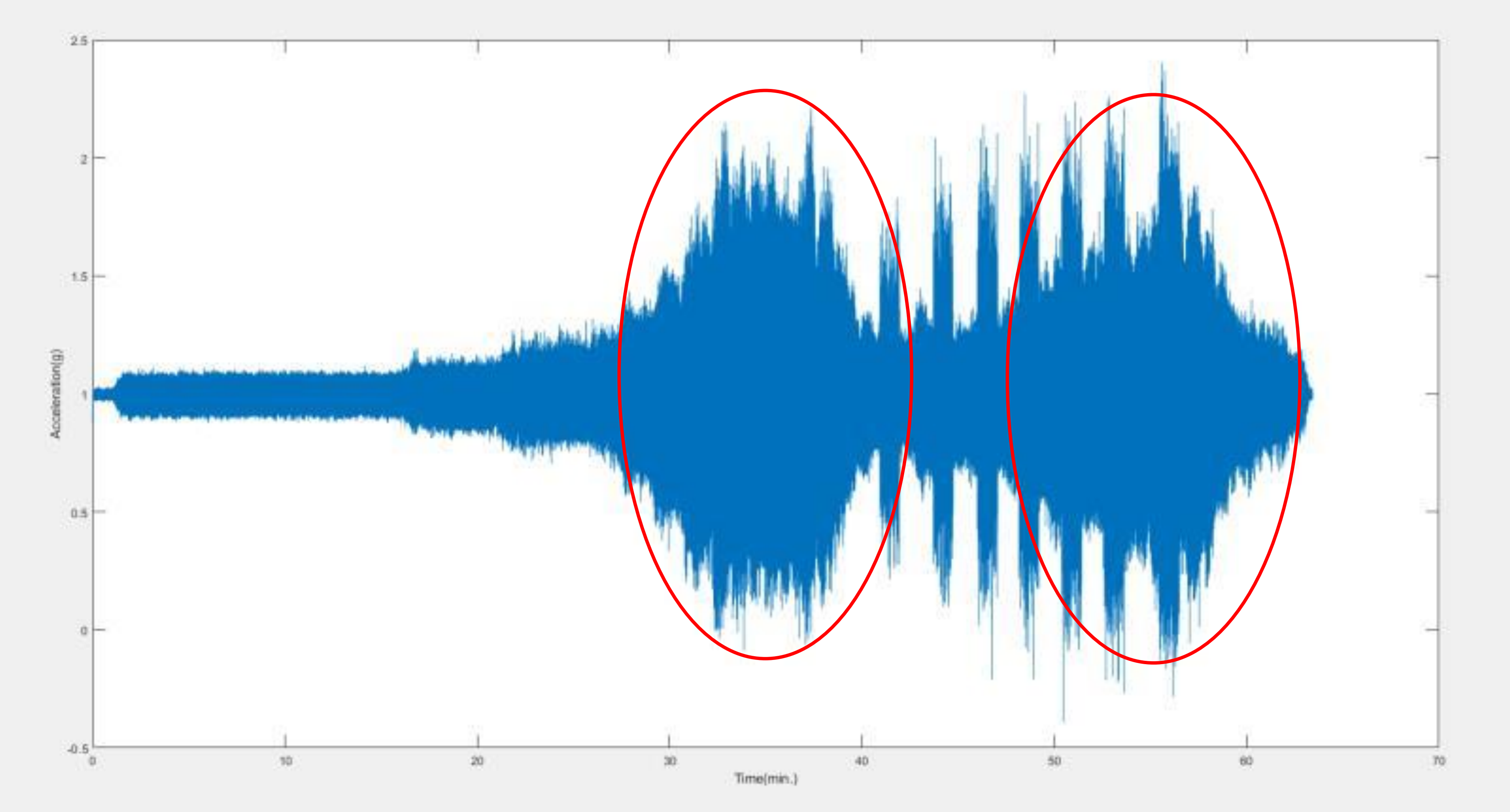
Our New Design in 2021 [6]

- **A full-scale rolling-vibration test was conducted in a train depot**

Full-scale testing (60-min) under various working conditions (Tri-axial vibration sensor deployed on bogie)

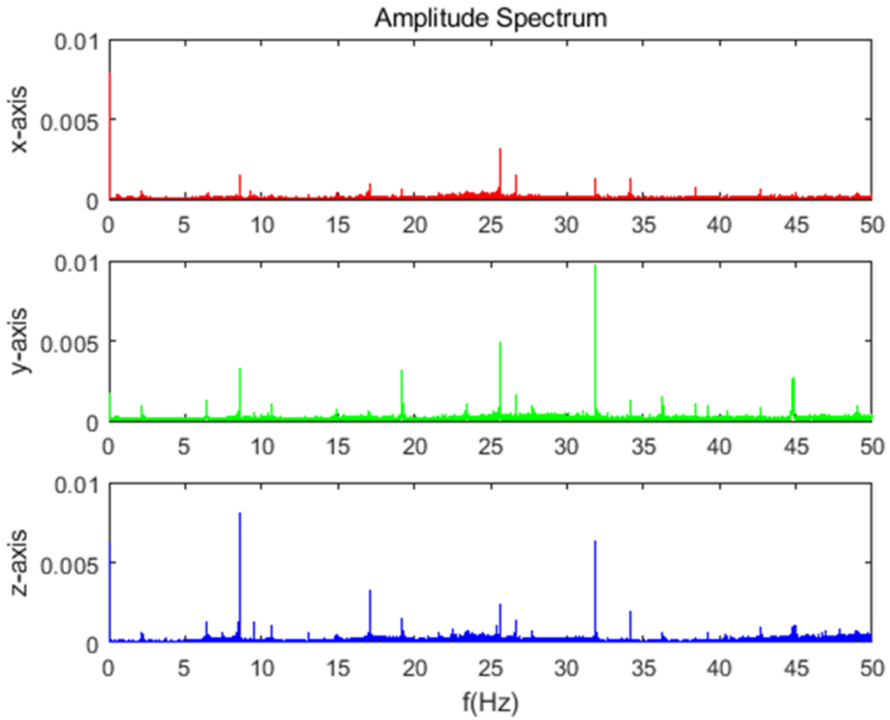
Time (min.)	Speed (km/h)	Working condition	Prototype (x,y,z)*
0-16	15		× × ×
16-17	50		× × ×
21-25	100		× × ×
26-29	150		× × ×
29-33	230	S-shaped excitation	× √ √
33-35	280		× √ √
36-38	300		√ √ √
38-40	deceleration to 120		√ √ √
40-42	120	vertical excitation	× √ √
44-46	180		× × ×
46-47	180	vertical excitation	√ √ √
47-48	200		× × ×
48-49	200	vertical excitation	√√√
49-50	220		× × ×
50-52	220	vertical excitation	√ √ √
52-52.5	230		× √ √
52.5-53.5	230	vertical excitation	√ √ √
53.5-55.5	250		× √ √
55.5-56.5	250	vertical excitation	√ √ √
56.5-60	deceleration		× × ×

*Based on the vibration data for preliminary analysis.



Time-history diagram for a 60-min vibration analysis at the bogie

Data analysis (100 km/h)

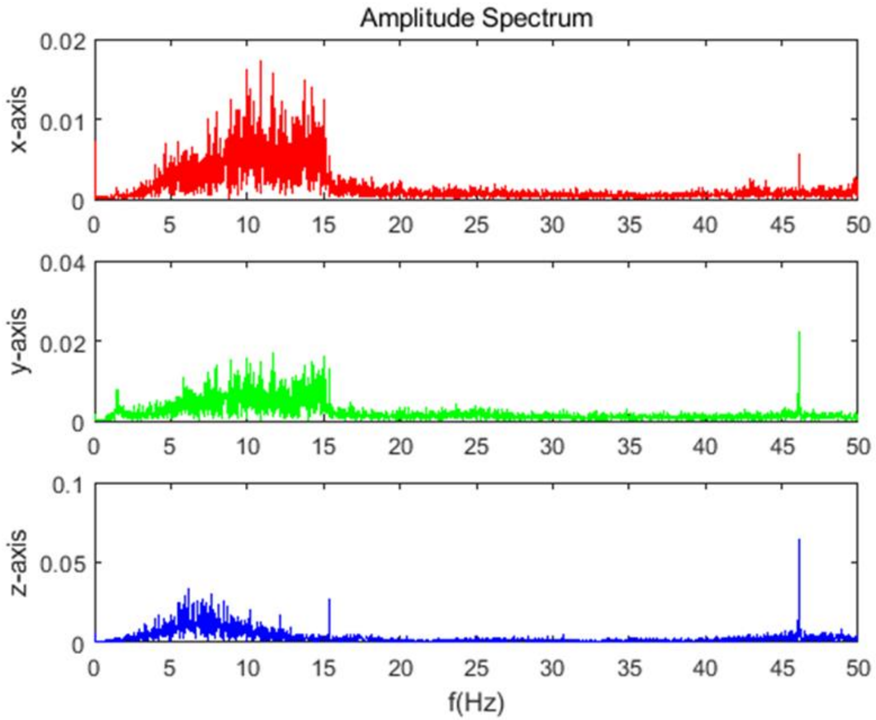


Speed – 100 km/h, acceleration response (g) along the x, y and z directions at the measurement point

> Speed 100 km/h (on test-bed)

- Except for small responses at 26.67 Hz, there are other small responses, e.g. at 8.53 Hz.
- The vibration intensity is still too small.

Data analysis (180 km/h)

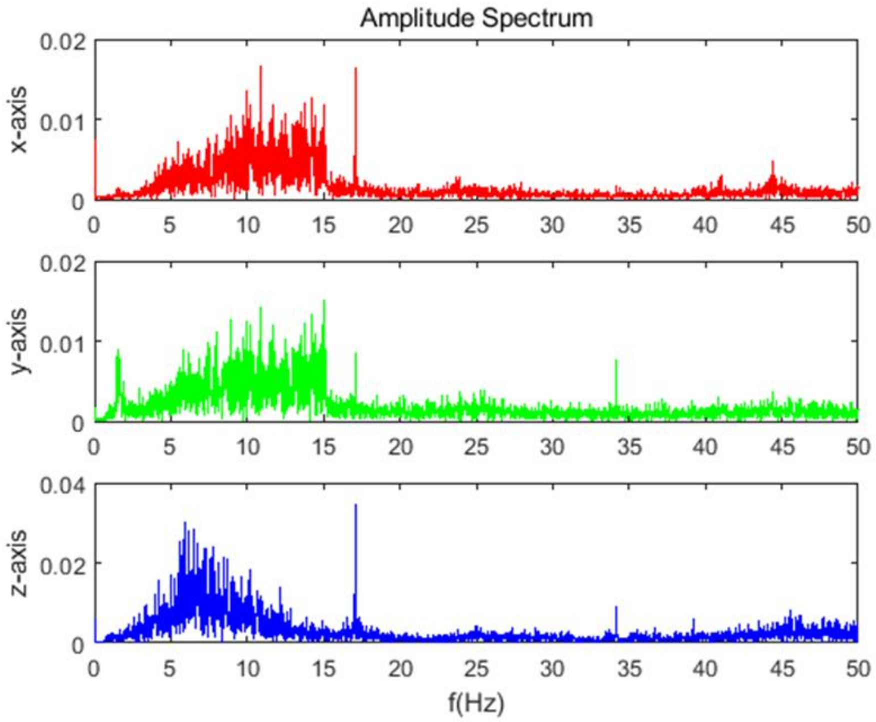


Speed – 180 km/h, with vertical excitation, acceleration response (g) along the x, y and z directions at the measurement point

> Speed 180 km/h (on test-bed, with a **vertical excitation**)

- At the speed of 180km/h with vertical excitation, there are broadband responses along all the three directions at the measurement point from 3.7Hz to 15Hz.
- The energy harvester prototype can harvest the energy along all the three directions effectively.

Data analysis (200 km/h)

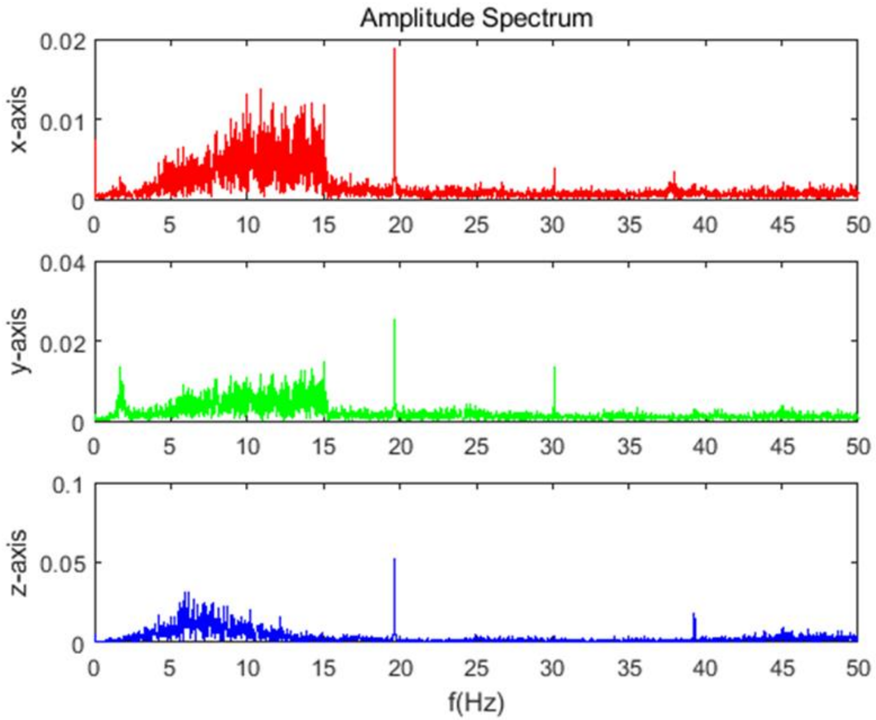


Speed – 200 km/h, with vertical excitation, acceleration response (g) along the x, y and z directions at the measurement point

> Speed 200 km/h (on test-bed, with a **vertical excitation**)

- At the speed of 200km/h with vertical excitation, there are broadband responses along all the three directions at the measurement point from 3.7Hz to 15Hz and a large response occurs at 17Hz.
- The energy harvester prototype can harvest the energy along all the three directions effectively.

Data analysis (250 km/h)



Speed – 250 km/h, with vertical excitation, acceleration response (g) along the x, y and z directions at the measurement point

> Speed 250 km/h (on test-bed, with a **vertical excitation**)

- At the speed of 250km/h with vertical excitation, there are broadband responses along all the three directions at the measurement point from 3.7Hz to 15Hz and a large response occurs at 21.35Hz.
- The energy harvester prototype can harvest the energy along all the three directions effectively.

Conclusions and Limitations

- The proposed energy harvester works well at a wide bandwidth of **1–11 Hz** under **1g**, with a maximum power of **86 mW**, that can power up different types of sensors.

- The testbed was not running on rails under operation. Vibration data are used for preliminary analysis.

- Vibration strength and frequency are much larger and wider under a real-life engineering condition.

- **On-going Work**:
  - ✓ Our energy harvesting device is being tested for on-board testing, results will be presented in a later stage.
  - ✓ How to pair the energy harvester with smart sensors and wireless data connections.

Thank you for your attention!