

Engineered metabarrier as shield from longitudinal waves: band gap properties and optimization mechanisms

Key words: Metabarrier; Phononic crystal; Band gap; Longitudinal wave; Optimization mechanism

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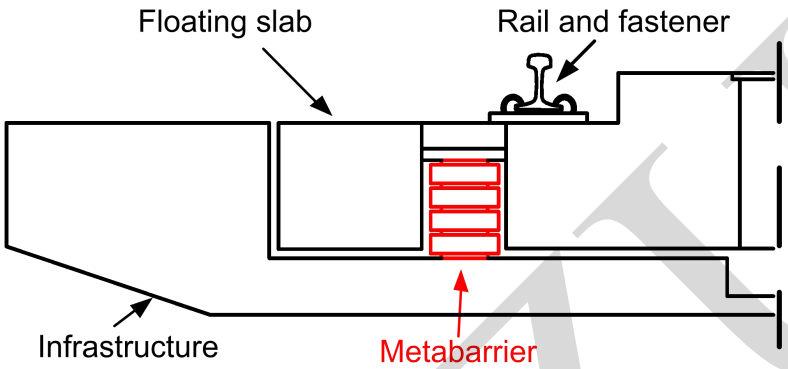
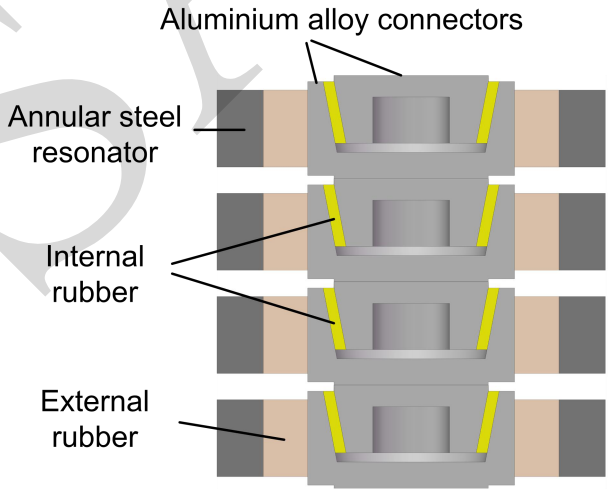
Proposed metabarrier

A metabarrier using a locally resonant phononic crystal mechanism is proposed for use as a floating-slab-track (FST) bearing to improve vibration mitigation performance, shielding infrastructure from low-frequency longitudinal waves which carry large vertical vibration energy and propagate vertically from the floating slab.



Layout of metabarrier in the FST



Geometry and material

- The proposed metabarrier is a one-dimensional phononic crystal structure set between the floating slab and the infrastructure.
- The external rubber and the annular steel resonator are designed to provide the locally resonant bang gaps (BGs) while the connectors and internal rubber are designed to provide the vertical stiffness for the floating slab.

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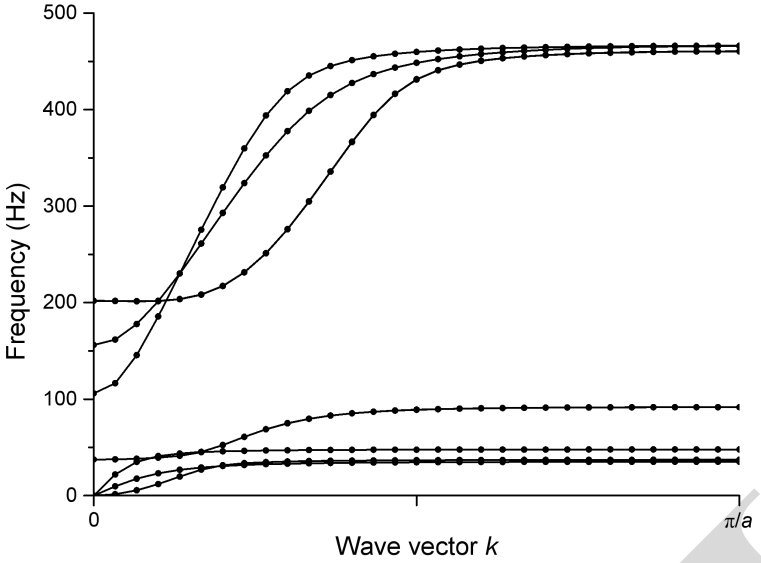
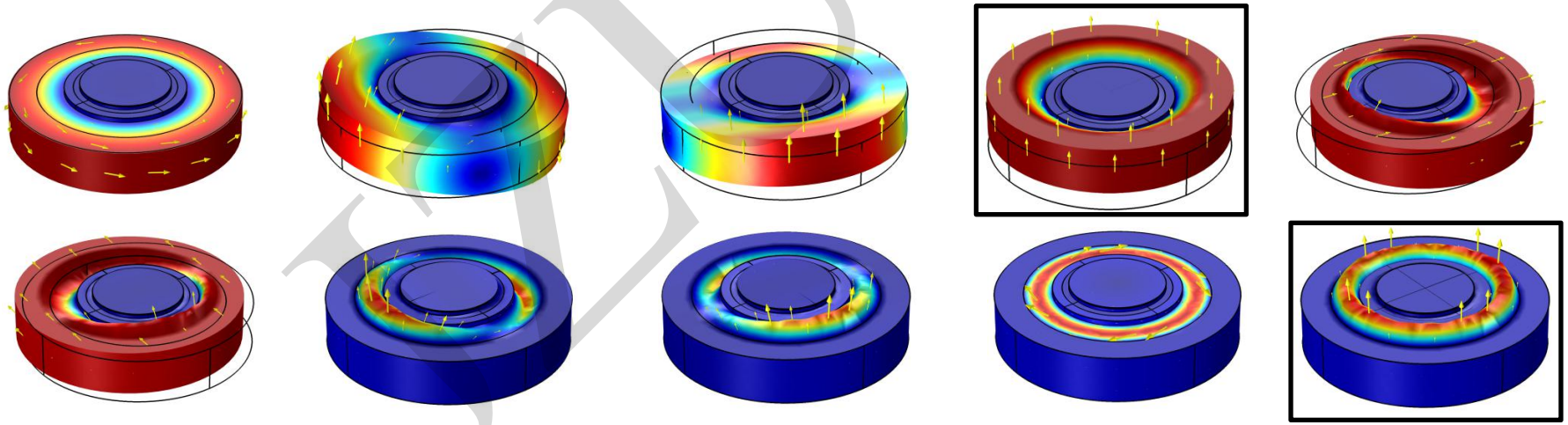
Band structure



The first ten band structure curves from the metabarrier

Though all the waves propagate along the axial direction (i.e. the vertical direction in the FST system), not all modes correspond to longitudinal waves, which are the major targets of the shielding. The modes of interest must be distinguished from others.



First 10 modes of the metabarrier ($k=\pi/a$)

The fourth and the tenth modes correspond to the longitudinal waves.

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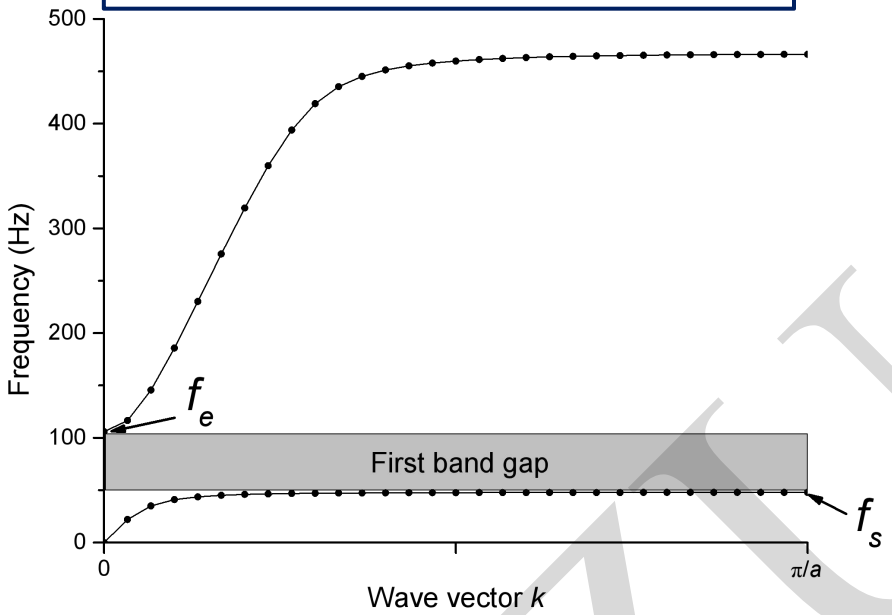
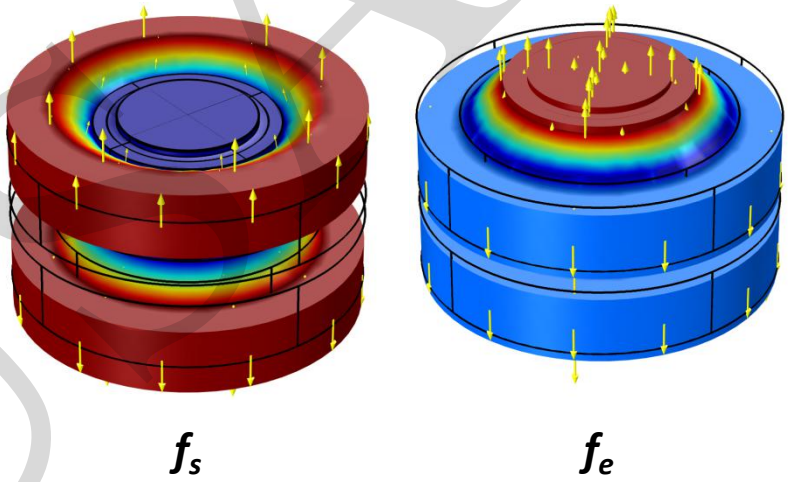
Band structure

Band structures after distinction



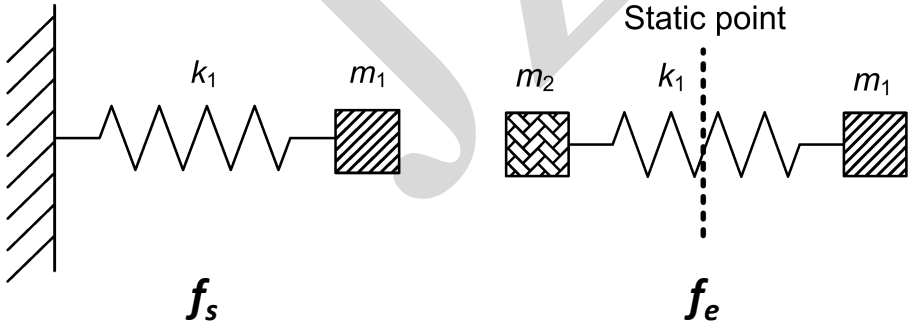
Modes corresponding to the starting frequency and the cut-off frequency



f_s f_e

The frequency range of the first BG was 48-105 Hz.

Simplified models of the starting frequency and the cut-off frequency in the first BG



$$f_s = \frac{1}{2\pi}\sqrt{\frac{k_1}{m_1}},$$

$$f_e = \frac{1}{2\pi}\sqrt{k_1\left(\frac{1}{m_1}+\frac{1}{m_2}\right)}.$$

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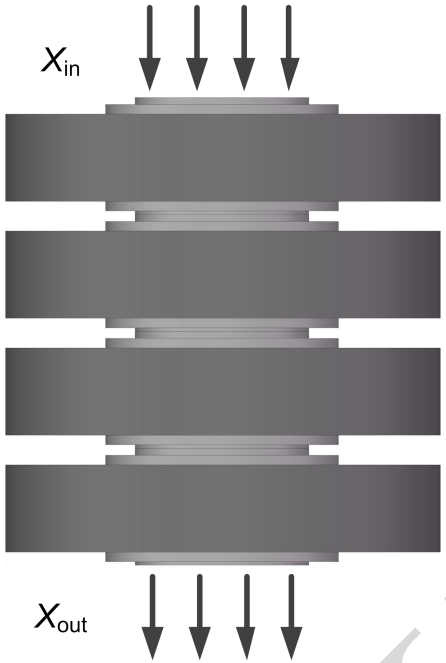
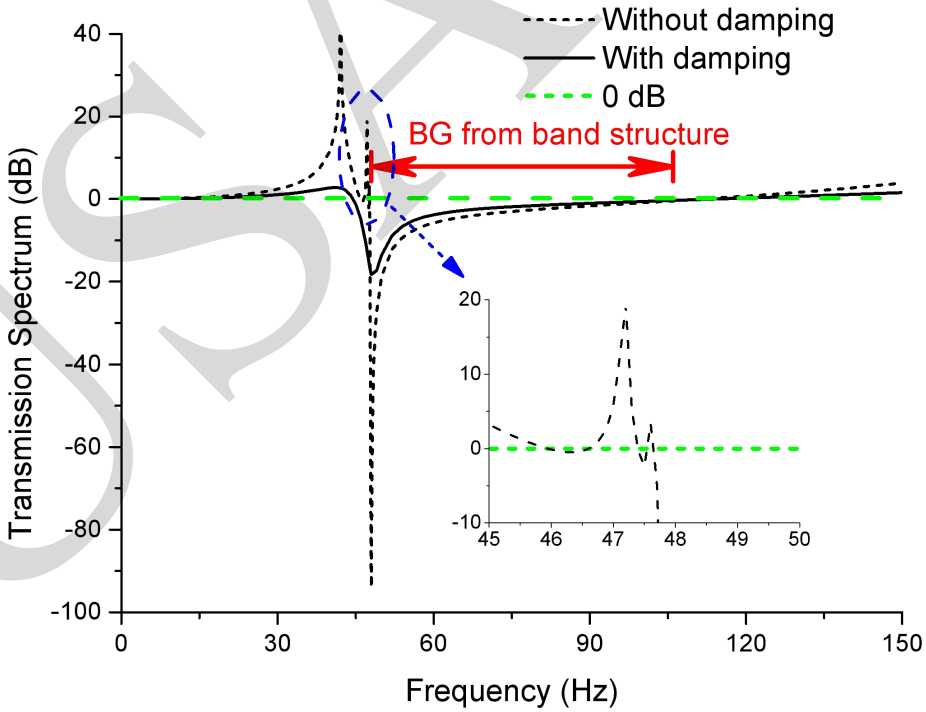
Shielding performance of the band gap

Transmission spectrum calculation of the metabarrier



$$TS = 20\log_{10}\left(\frac{|X_{out}|}{|X_{in}|}\right).$$



- A transmission spectrum was used to verify the shielding performance of the BG.
- The first BG frequency range matched well with the shielding zone obtained by the transmission spectrum.
- Additionally, the vertical static stiffness of the metabarrier was 6.0 kN/mm, which is close to that of existing steel-spring vibration isolators. The vibration isolation performance of a traditional FST is retained.

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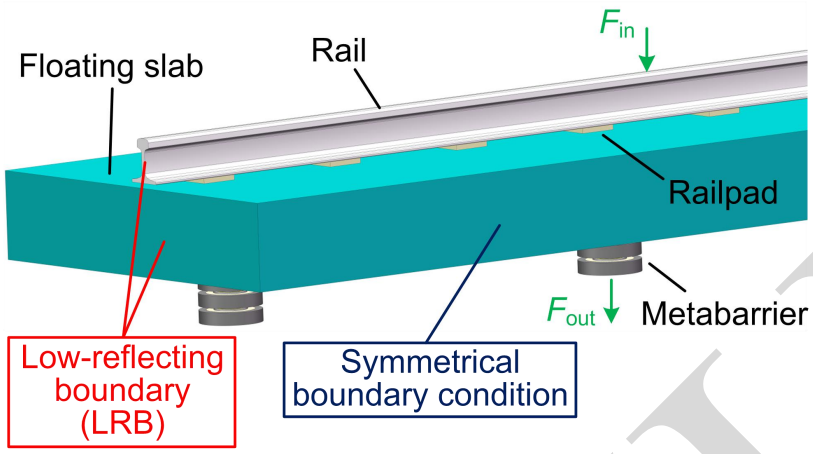
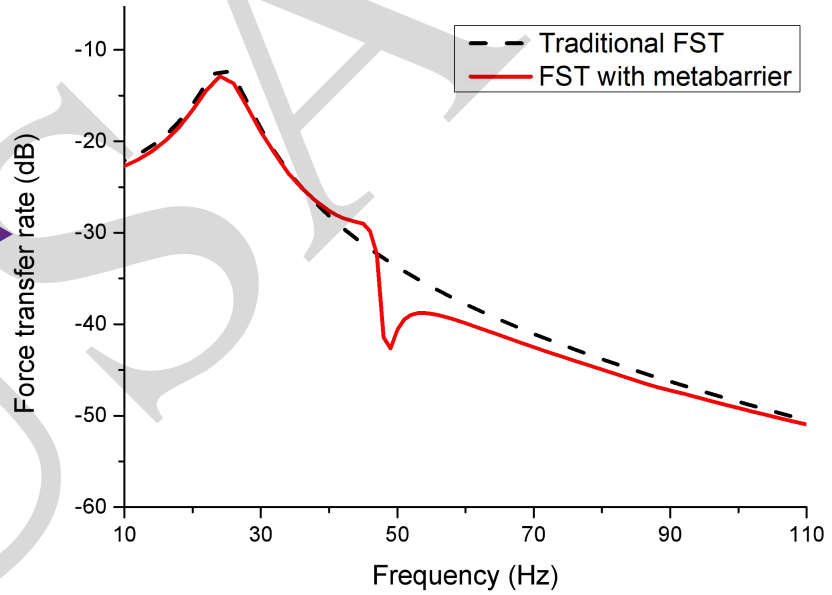
Overall vibration mitigation performance

Calculation of the force transfer rate



$$FTR = 20\log_{10}\left(\frac{|F_{out}|}{F_0}\right)$$

Force transfer rates of two types of tracks



- The force transfer rate of the FST with the metabarrier was lower in the frequency range of 47-110 Hz, and therefore the vibration mitigation performance was enhanced.
- Through the optimization of the band gap boundary frequencies, the frequency range of the enhancement could be controlled.
- The retained vibration isolation performance of the low natural frequency, the shielding performance of the band gap and the controllability of band gap boundary frequencies all contributed to an improvement in overall vibration mitigation performance.

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Multi-objective optimization of the boundary frequencies

A better shielding performance can be achieved if the dominant frequency range of ground-borne vibrations induced by subways is within a wider BG.

Multi-objective genetic algorithm

The objectives of the multi-objective optimization problem (MOP) were to lower the starting frequency and widen the BG:

$$\min f_s,$$

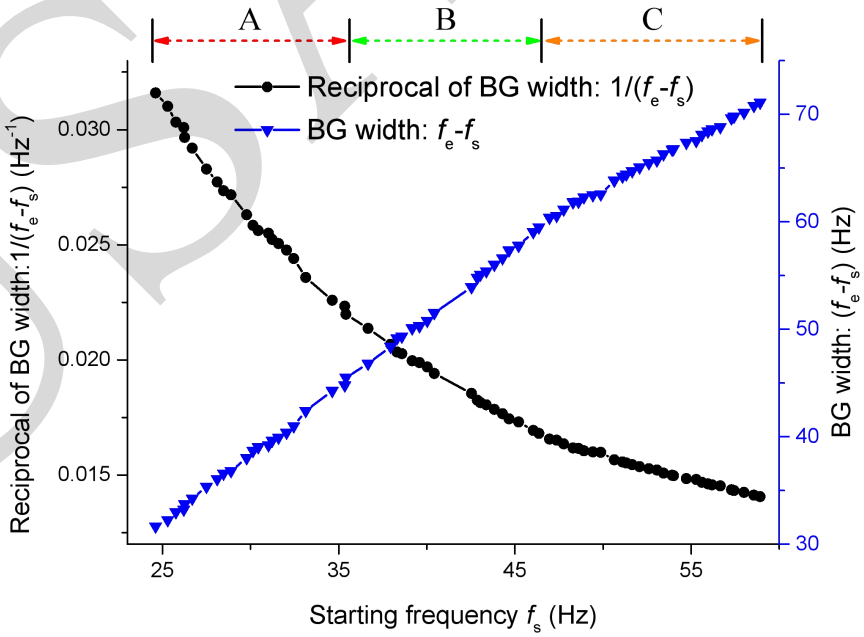
$$\min \frac{1}{f_e - f_s},$$

Parameters requiring optimization were a_4 and E_3, and the constraints of the parameters were as follows:

$$25\ \text{mm} \le a_4 \le 35\ \text{mm},$$

$$1\ \text{MPa} \le E_3 \le 4\ \text{MPa}.$$

Pareto Front of the MOP



Partial Pareto optimums of the MOP

a_4 (mm)	E_3 (MPa)	f_s (Hz)	f_e-f_s (Hz)
33.4	3.76	49	62
31.0	3.56	50	63
31.8	3.79	51	64
30.9	3.79	52	65

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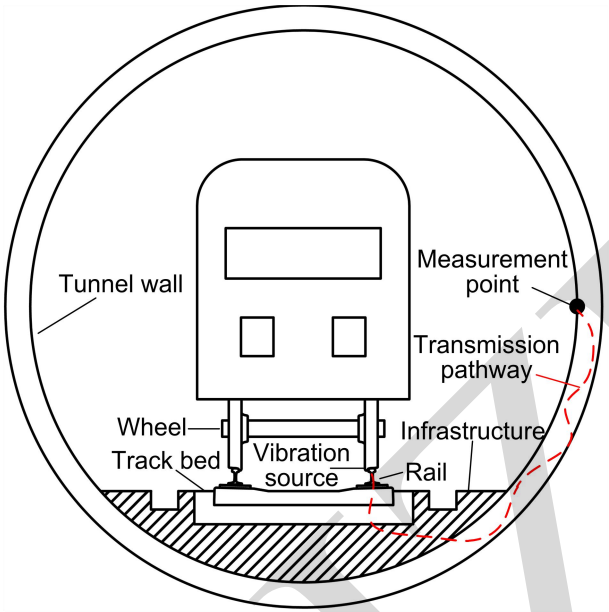
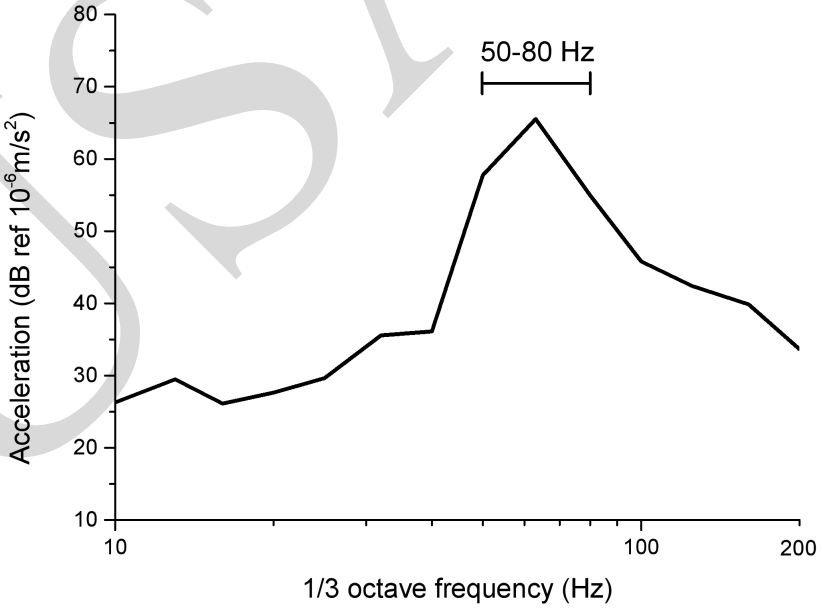
Multi-objective optimization of the boundary frequencies

It is necessary to optimize the BG boundary frequencies according to the train-induced vibrations.

Train-induced vertical acceleration response on the tunnel wall





- The response was used as a survey to reflect the characteristics of ground-borne vibrations.
- There was a peak in the frequency range of 50~80 Hz, which was therefore the dominant frequency range.
- The starting frequency was chosen to be 50 Hz, and the corresponding optimal width of the BG was 63 Hz with the Pareto optimum of a_4=31.8 mm and E_3=3.79 MPa.

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Conclusions

- The metabarrier can generate a low-frequency locally resonant BG to shield infrastructure from the longitudinal waves from a floating slab. The vertical static stiffness of the metabarrier is close to that of existing steel-spring vibration isolators. The retained vibration isolation performance of the low natural frequency, the shielding performance of the band gap and the controllability of band gap boundary frequencies all contribute to the overall vibration mitigation performance.

- Simplified models showed that the starting frequency of the first BG is determined by the resonance of the steel resonator. The cut-off frequency of the first BG is determined by the resonance between the steel resonator and the combination of connectors and internal rubber.

- The vertical stiffness and the first BG boundary frequencies of the metabarrier can be independent. The first BG frequency range matches well with the shielding zone obtained by the transmission spectrum.

- The simplified models can be used for the MOP to obtain a wider and lower BG. By the use of a genetic algorithm, the BG was chosen to be 50~113 Hz from the Pareto optimal set according to the dominant ground-borne vibrations induced by subways.

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