Advanced high-speed train suspension for simultaneous vibration control and energy harvesting

Prof. Songye Zhu

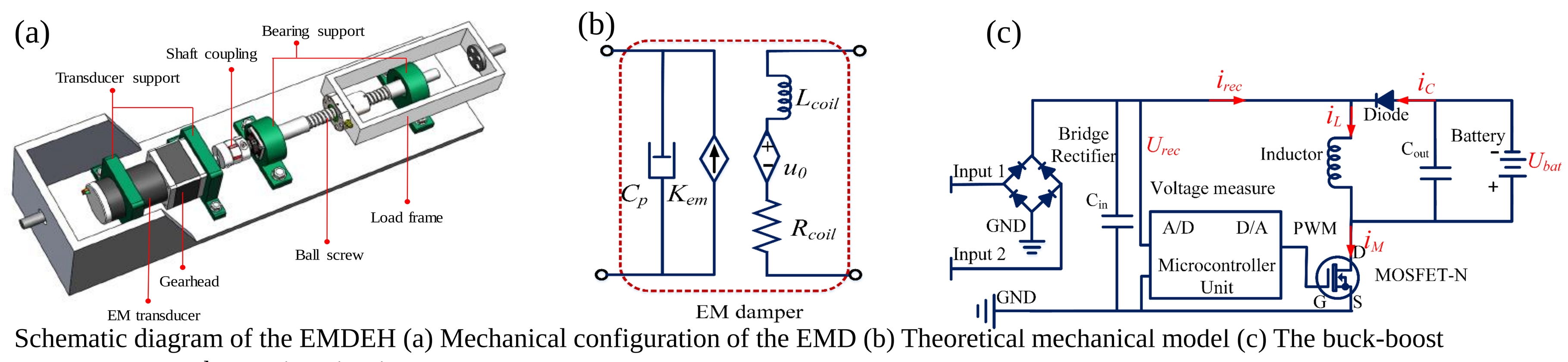
Department of Civil and Environment Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China

Adaptive and semi-active suspension with energy harvesting performance

- The effectiveness of the passive suspension is limited, given the increasing train speed as well as the wide and variable frequency range of excitations induced by track irregularities.
- The active or semi-active suspension can adapt to a broad excitation frequency range. However, the power consumption hinders their widespread acceptance.
- Compared to traditional semi-active suspension, the proposed suspension is associated with the advantages of energy regeneration and adaptive vibration control.

Electromagnetic damper cum energy harvester(EMDEH)

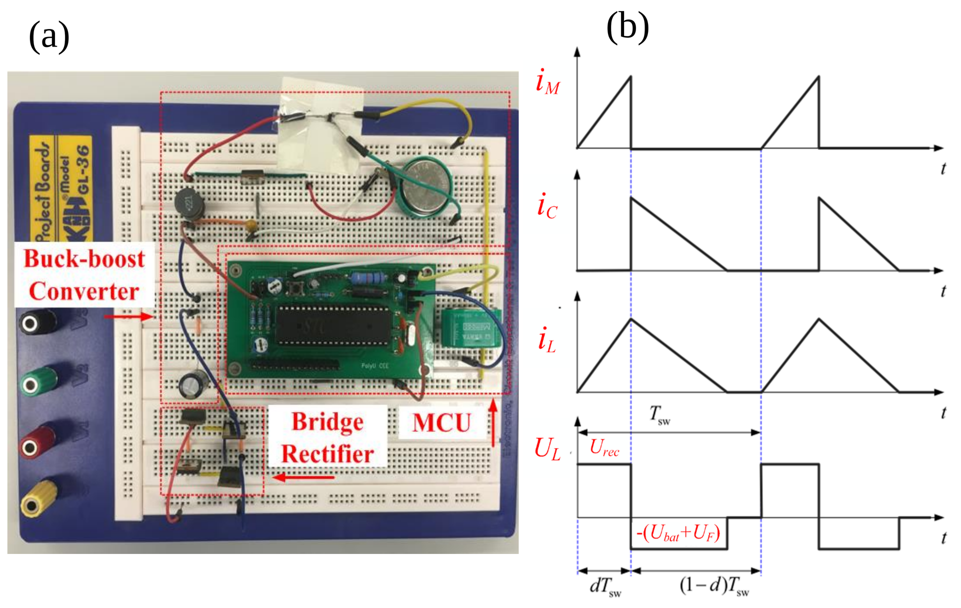
- The EMDEH consists of the EM transducer (EMD) providing the mechanical damping force and the buck-boost converter energy harvesting circuit (EHC) for energy extraction.
- The microcontroller unit (MCU) adjusts the equivalent resistance of EHC.



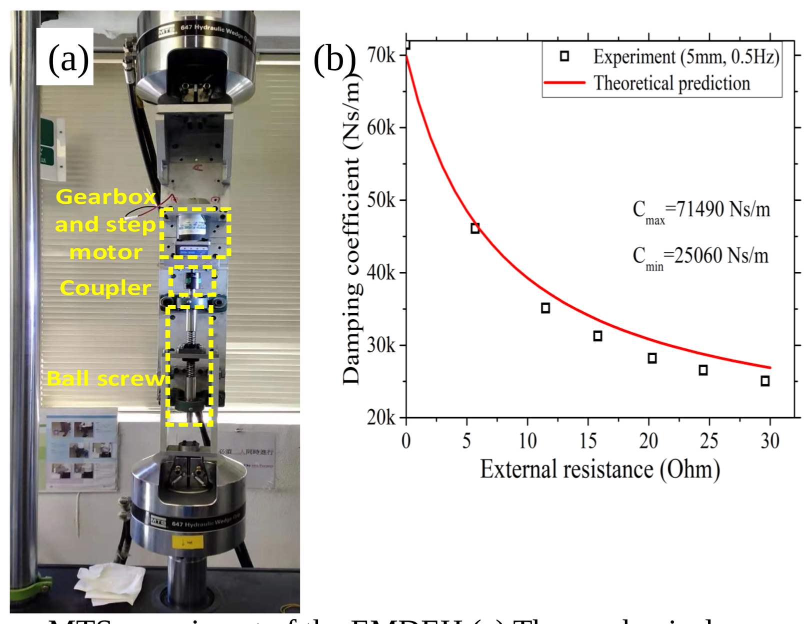
Schematic diagram of the EMDEH (a) Mechanical configuration of the EMD (b) Theoretical mechanical model (c) The buck-boost converter energy harvesting circuit

Experimental validation of adjustable resistance and controllable damping

- The equivalent resistance of the EHC can be flexibly adjusted by the PWM signal under the DCM operation mode.
- The varying damping coefficient of the EMDEH prototype against external resistance ranges from 25 kNs/m to 71 kNs/m.



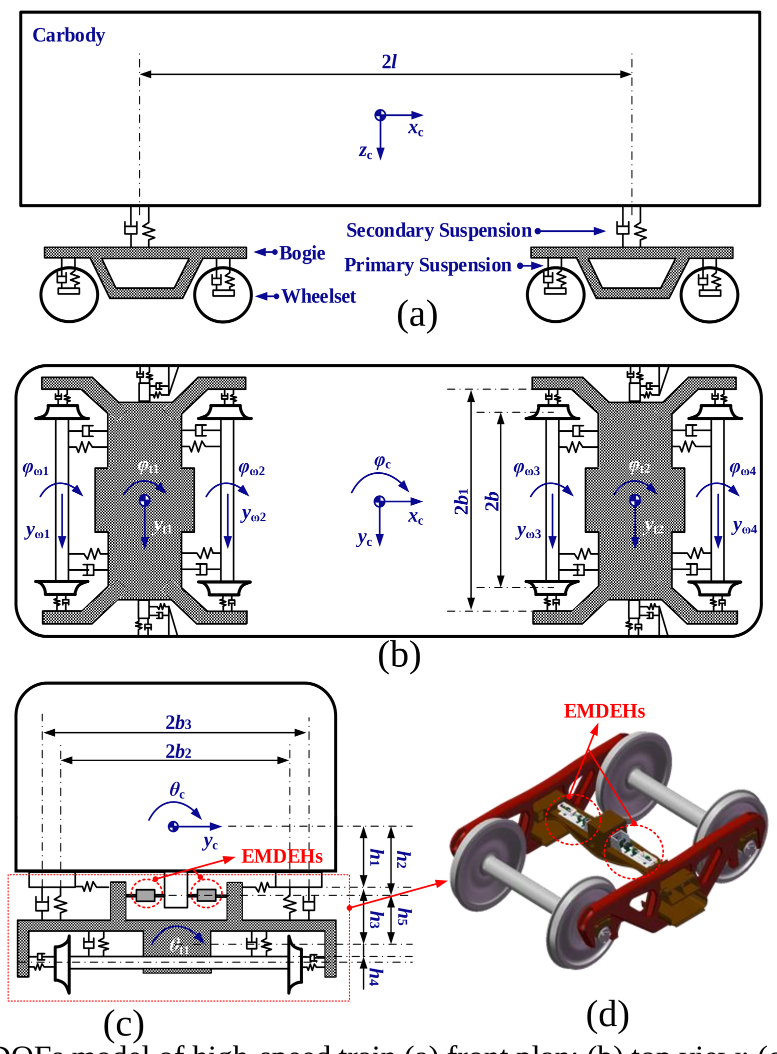
Experimental setup of the energy harvest circuit (a) The buck-boost converter with an MCU board; (b) Waveforms of the DCM buck-boost converter;



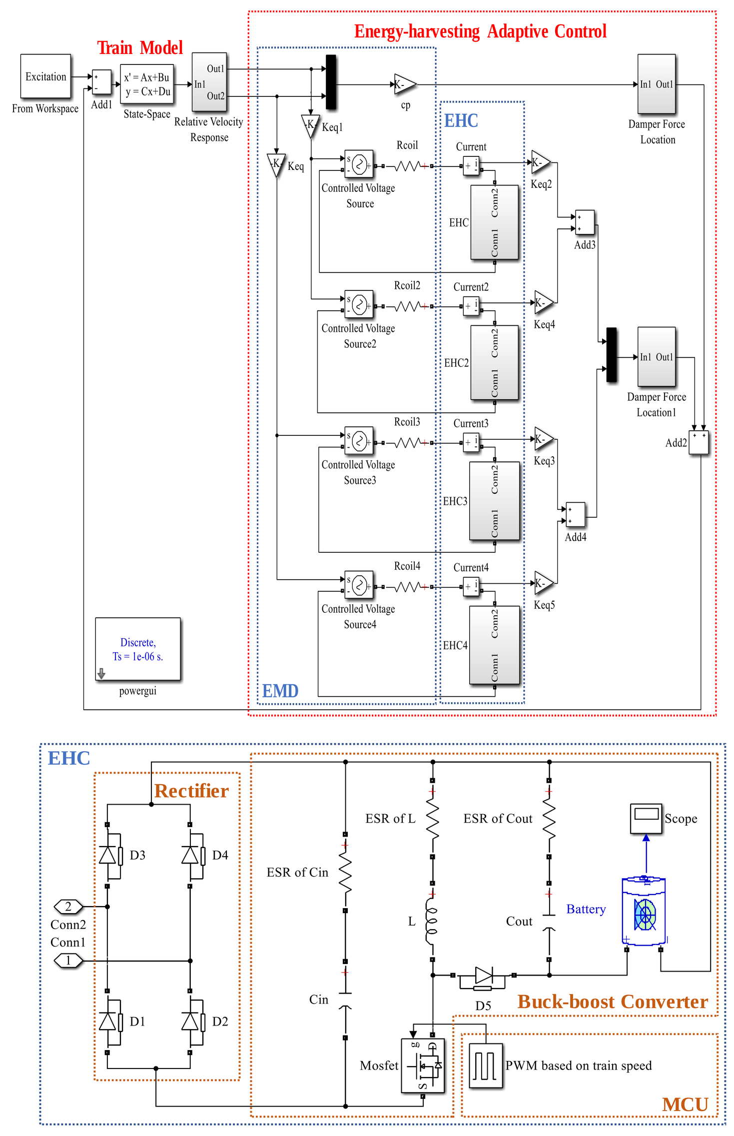
MTS experiment of the EMDEH (a) The mechanical components of the EMD; (d) Varying damping coefficient of the EMD against external resistance

High speed train integrated with EMDEH

- The 17DOFs HST model consists of one car body, two bogies and four wheelsets.
- The EMDEHs are installed in the secondary lateral suspension to replace the passive viscous dampers.



17 DOFs model of high-speed train (a) front plan; (b) top view; (c) Profile plan; (d) EMDEH installed in the secondary suspension



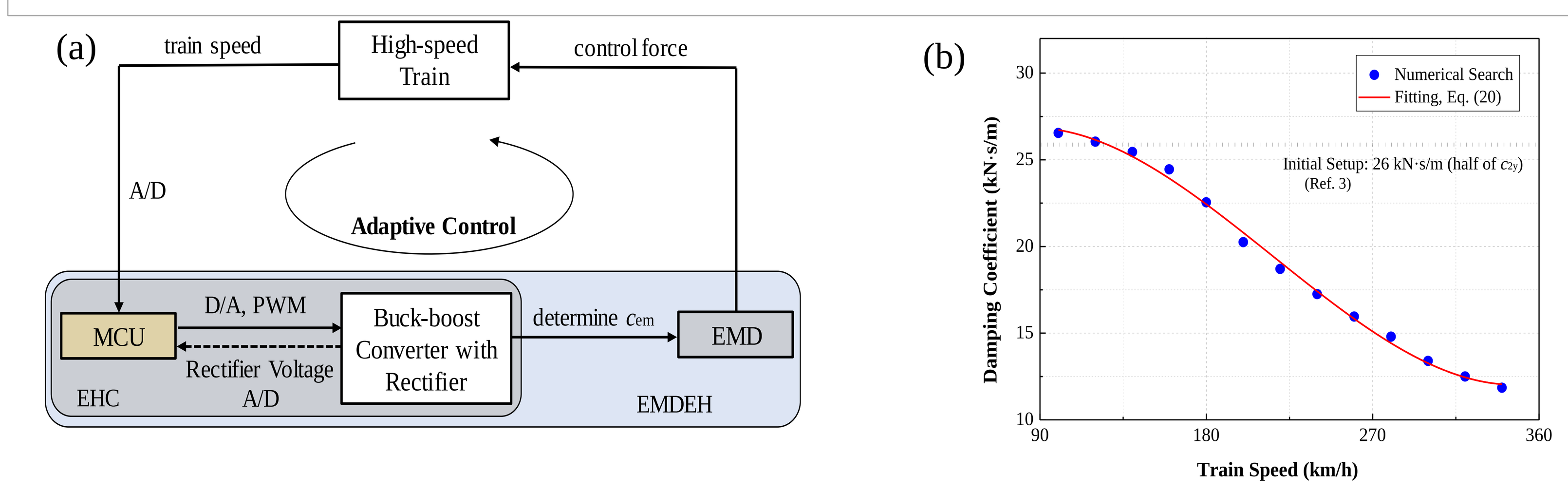
Simulink model for HST with EHAC

Main parameters of the EHC

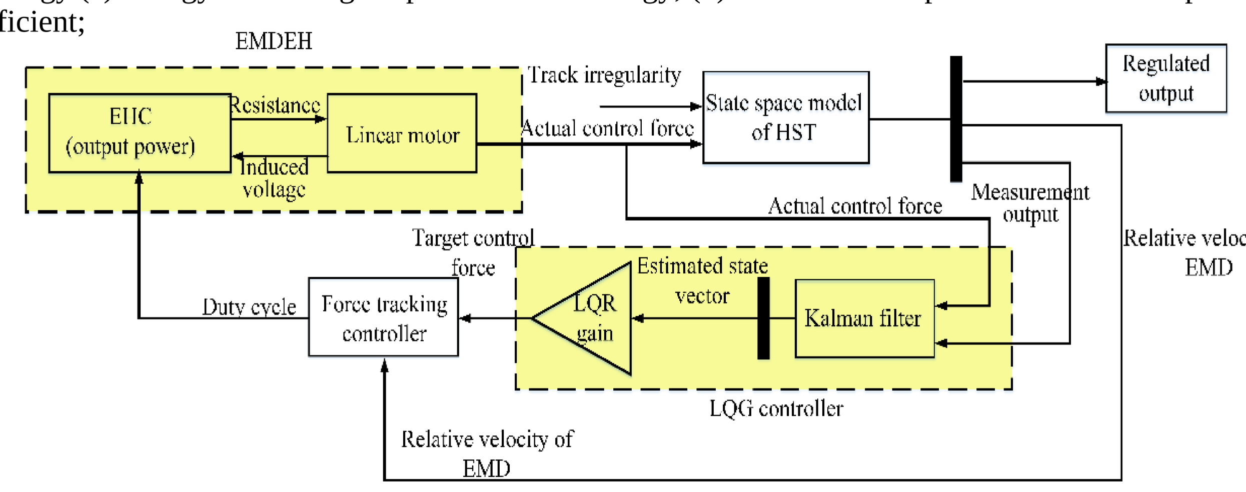
Parameter	Value	Parameter	Value
Filter capacitor, C_{in}	240 μF	Switch frequency, f_w	20 kHz
ESR of filter capacitor, $R_{esr,in}$	0.2 Ω	Forward voltage of diode, U_F	0.22 V
Inductor, L	100 μH	Static drain-source on resistance of the MOSFET, R_{on}	0.8 Ω
ESR of inductor, $R_{esr,L}$	0.53 Ω	Nominal voltage of rechargeable battery, U_{bat}	110 V
Output capacitor, C_{out}	10 μF	Power consumption of MCU	ignored
ESR of output capacitor, $R_{esr,out}$	0.18 Ω		

Development of control strategy

- In the energy-harvesting adaptive control (EHAC), the duty cycle of PWM waves in the EHC is adaptively adjusted based on the train speed, and thus the buck-boost converter can always emulate a target resistance and produce an optimal equivalent damping coefficient within the concerned train speed range, wherein the optimization objective is to minimize the RMS lateral acceleration of the car body.
- In the semi-active control strategy, the PWM signal is adjusted transiently by the force tracking controller of the EMD to track the target LQG controller force. Consequently, the semi-active suspension could achieve vibration control performance to the LQG controller with energy harvested simultaneously.



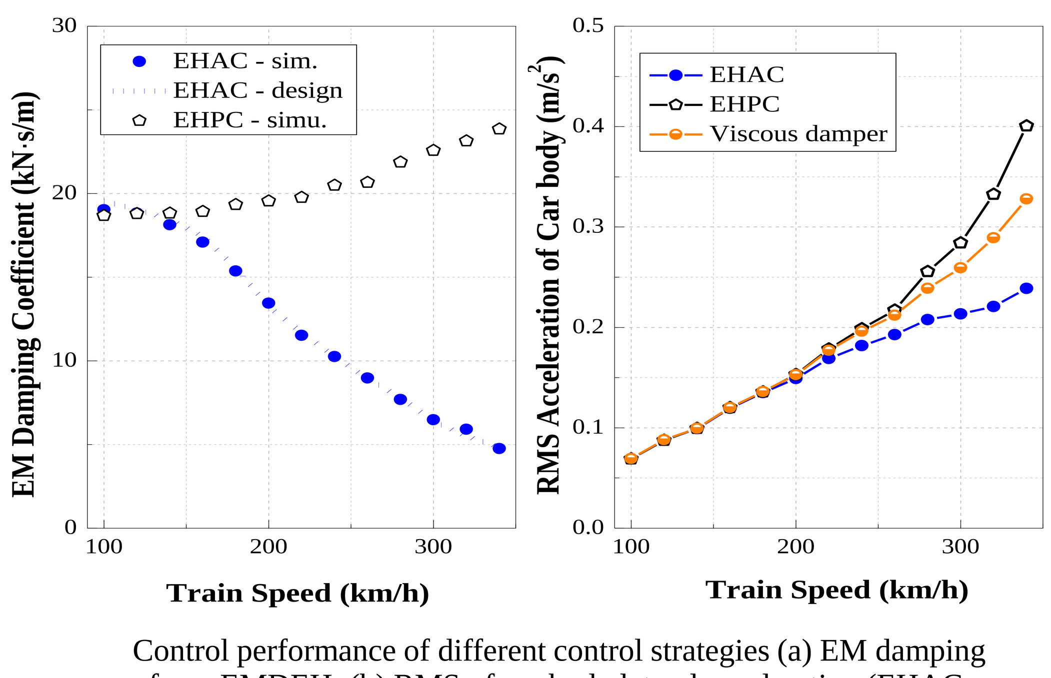
The adaptive control strategy (a) Energy-harvesting adaptive control strategy; (b) The relationship between the train speed and the optimum damping coefficient;



Semi-active LQG control strategy of EMDEH implemented in the high-speed train suspension

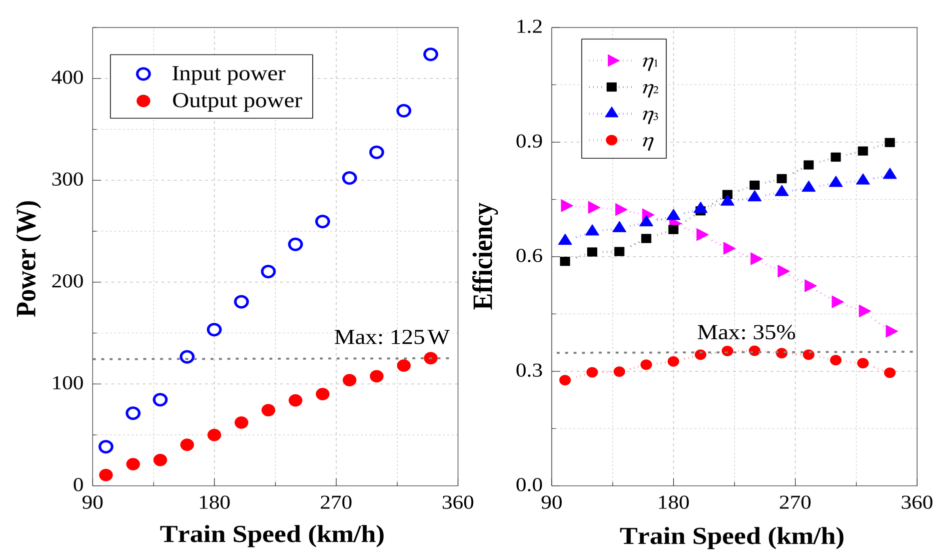
- The output power in the case of EHAC ranges from 40.5 W to 589.8 W within the considered train speed (100–340 km/h), which will likely be sufficient to power numerous wireless sensors for train monitoring or MCUs used in semi-active/active vibration control.
- The numerical results demonstrate the potential of EMDEH implemented in the high-speed train to power numerous wireless sensors for train monitoring or MCUs used in semi-active/active vibration control.

Energy harvesting and vibration control performance

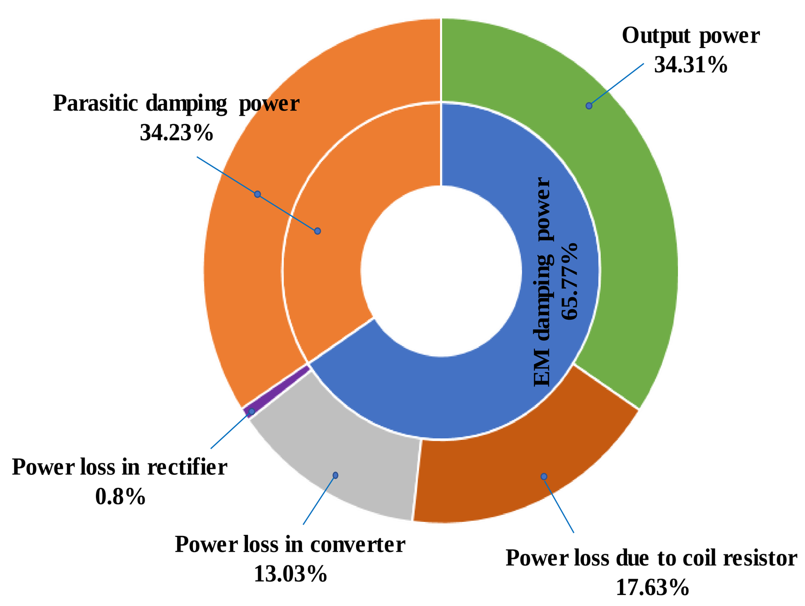


Control performance of different control strategies (a) EM damping of one EMDEH; (b) RMS of car body lateral acceleration (EHAC: adaptive control strategy; EHPC: fixed duty cycle EMD)

- Compared with EHPC, EHAC can improve the vibration control performance by 40% at a high train speed.
- The EHPC shows similar control performance to passive control at a low train speed, but results in worse vibration control performance at a high train speed due to the influence of the CCM operation mode.



Harvesting performance in different train speeds: EHAC (a) Power; (b) Efficiency



Power distribution of input power under 200 km/h

Harvesting results of EHAC and EHPC (4 EMDEHs) under three different train speeds

Train Speed (km/h)	EHAC		EHPC	
	Output Power (W)	Output Efficiency (%)	Output Power (W)	Output Efficiency (%)
100	40.47	27.56	41.62	28.12
200	244.92	34.28	242.02	29.19
300	469.84	32.88	690.66	24.59
340	589.82	30.27	1046.24	22.09