SHORT COMMUNICATIONS

Cylinder-based hybrid rotary nanogenerator for harvesting rotational energy from axles and self-powered tire pressure monitoring

Jian He1 | Shengli Cao2 | Hulin Zhang2,3

1Science and Technology on Electronic Test and Measurement Laboratory, North University of China, Taiyuan, China
2Key Lab of Advanced Transducers and Intelligent Control System of the Ministry of Education & College of Information and Computer, Micro Nano System Research Center, Taiyuan University of Technology, Taiyuan, China
3State Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronic Science and Technology of China, Chengdu, China

Correspondence
Hulin Zhang, Key Lab of Advanced Transducers and Intelligent Control System of the Ministry of Education & College of Information and Computer, Micro Nano System Research Center, Taiyuan University of Technology, Taiyuan 030024, China.
Email: zhangd198710@gmail.com

Abstract
Tire pressure monitoring plays a pivotal role in vehicle safety system. However, as a conventional battery-operated electronic system, regularly replacing battery remains a great inconvenience in wide-distributed tire pressure sensing. Here, we introduce a self-powered tire pressure monitor by using a rotary cylinder-based hybrid nanogenerator as a sustainable power source. The designed energy harvester, by hybridizing a triboelectric nanogenerator (TENG) and electromagnetic generator (EMG), can scavenge rotational energy from rolling axles. Integrating with transformers, the hybrid nanogenerator can achieve an open-circuit voltage of 16 V and short-circuit current of 0.1 mA at the rotation rate of 150 rpm, respectively, with the maximal output power of about 1.8 mW at the loading of 20 kΩ. Via a programmable software, the hybrid device can operate as a self-powered counter and timer for potential speed detecting. Further, it has been demonstrated that the hybrid nanogenerator is capable of triggering a transmitter-integrated tire pressure sensor for self-powered monitoring tire pressure in real time. This study expands applications based on TENGs in automobile engineering, which might promote the development of intelligent driving and traffic safety engineering.

KEYWORDS
hybrid nanogenerator, self-powered, tire pressure monitoring, triboelectric nanogenerator

He and Cao equally contributed to this work.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2019 The Authors. Energy Science & Engineering published by the Society of Chemical Industry and John Wiley & Sons Ltd.

Energy Sci Eng. 2020;8:291–299.
1 | INTRODUCTION

Mechanical energy is quite abundant in our living environment with the considerable availability both in location and time.1-3 Although a series of techniques, such as piezoelectric nanogenerators, electrostatic generators and electromagnetic generators, has been utilized for harnessing diverse mechanical energy, most of them individually are relatively low-efficiency or of complex preparation.4-7 Since TENGs were invented by Zhong Lin Wang’s group in 2012,8-14 inspired from triboelectrification, TENGs have been proved to be simple, cost-effective, and feasible to harvest environmental mechanical energy.15-20 Plenty of various TENGs has been demonstrated to grab diverse types of mechanical energy, such as vibration, rotation, translational motion, sliding, and so on.21-26 Besides, conventional EMGs have been used widely in industrial production. Pint-sized EMGs are quite sensitive to operating frequency and have non-negligible disadvantages of large mass and low output voltage, while TENGs usually possess a relatively high output voltage with a low current.27-29 Hence, the hybridization of the two generators is imperative which can realize complementarity. Concretely, by combining of a TENG and EMG, the individual advantages can be integrated while the disadvantages are avoided. As a hybrid device, the desirable high voltage and current are primarily important. Not only that, the portable and mobile property might be delivered via a configuration optimization to improve its usability of the energy harvesting device. In practice, a superior hybridization between different nanogenerators is a pivotal goal for energy harvesting scientists. In spite of that there have been a few reports on combination of a TENG and EMG, it is necessary to explore novel hybrid energy harvesters with reasonable configurations, which can collect environmental energy efficiently.

Aimed at providing advanced sensing information and control technologies related to different transportation modes and even vehicle monitoring, the tire pressure monitor is deemed one of the three major safety systems in automobiles.30-36 The first tire pressure monitoring system operates by comparing rotation rates of four wheels. Once one of the wheels differs from others in rate, the trip-computer system will give an alarm. Clearly, this technique lacks of reliability and stability to some extent in a complex road environment. The other approach is to install battery-operated pressure sensors inside tires by which the pressure datum can be sent out directly. Nevertheless, the high cost and inconvenience of regularly replacing battery put a severe obstacle on its widespread application.37-43 Hence, a sustainable self-powered tire pressure detector is particularly urgent for timely vehicle monitoring.

In this work, we have assembled a rotary cylindric triboelectric-electromagnetic hybridized nanogenerator that can harvest rotational energy efficiently. Via a programmable software, the hybrid device can operate as a self-powered counter and timer for potential speed detecting. In addition, the hybrid nanogenerator has been demonstrated to be capable of triggering a transmitter-integrated tire pressure sensor for self-powered monitoring tire pressure in real time. This work presents solid progress toward the feasible TENG-based applications in automotive engineering, mechanical engineering, as well as and automation.

2 | EXPERIMENTAL SECTION

The basic framework of the hybrid device was made of acrylic sheets (4 mm in thickness) that were processed by laser cutting. The tailored PTFE strips (4 mm × 5 cm) were attached on the individual sponge rotator, while the Al foils serving as electrodes were adhered evenly to inner surface of the acrylic cylinder. Both the PTFE film and Al foil have a thickness of 110 μm. Four pairs of cylindrical magnets (2 cm in diameter and 5 mm in thickness) and coils (2 cm in diameter and 3 mm in thickness) were, respectively, embedded uniformly in the acrylic substrate. The four acrylic blades can rotate freely by being fixed with the central axle. In the electrical measurement, the axle and a drive motor (the rotation rate is continuously adjustable in the range of 0-1000 rpm) are soldered together.

The voltage and current were recorded by using a Keithley 6514 electrometer (200 TΩ in input resistance) and SR570 low-noise current amplifier (Stanford Research System). All the used capacitors, resistors, transformers, and Li-ion batteries (10 mAh) are commercially purchased without further treatment. In the self-powered demonstration, the software interface was programmed on a Labview platform. The counting and timing modules can display the actual number and time duration in real time. By integrating the nanogenerator with a commercial pressure sensor, the pressure in a basketball and tire can be detected and sent to a teleterminal without using any external power sources.

3 | RESULTS AND DISCUSSION

Figure 1A depicts a basic schematic diagram of the rotary hybrid nanogenerator with a cylindric configuration. Four tailored PTFE strips anchoring on sponge-covered acrylic blades and Al foils adhered on inner surface of the cylinder compose a rotary TENG. However, four magnets with the same polarity orientation are uniformly anchored on acrylic intercrossing blades as a rotator, with four coils attached on cylindric surface serving as a stator, forming an EMG. The AFM image shows that the PTFE possesses a coarse surface, which can enhance triboelectrification between tribo-layers owing to a higher surface charge density.44 Figure 1B portrays...
the output voltage and current generated by the TENG. At the rotation rate of 150 rpm, the TENG can nearly have an open-circuit voltage of 35 V and short-circuit current of 1 μA, respectively. It is known that the practical output power is associated with actual load. As shown in Figure 1C, the output voltage increases continuously while the power rises firstly and then decreases as the loading resistance goes up. At a load resistance of 80 MΩ, the maximal power of 5.3 μW can be acquired. As for the EMG, as plotted in Figure 1D,E, it is observed a peak voltage of 7 V and current of 6.5 mA, respectively. As the external resistance gradually rises, the output current declines observably while the output power possesses the same variation trend with the TENG, with a supreme output power of 0.41 mW got at the loading of 30 Ω. Because of the larger internal impedance of the TENG, it delivers a larger output voltage compared to its lower output
current, while the EMG possesses an inverse feature with a lower internal resistance. The TENG is considered as a current source with a large internal resistance. Due to that the electrostatic induction is a redistribution of electrical charges in object caused by the influence of nearby charges to fully balance the electric field, the interfacial potential difference will drive electrons flow in order to cancels the tribo-charge-induced potential. While, the EMG is equivalent to a voltage source with a small internal resistance with the fundamental principle of the electromagnetic induction that depends on the variation of magnetic flux. According to the previous investigation, for sake of an efficient integration of the electrical outputs from two generators, transformers were employed to tune the electrical output of the EMG, in order to reduce the difference of internal resistance. Figure 1F,G display that the peak voltage and current can reach 14 V and 0.1 mA respectively in the same condition. Meanwhile, the output voltage and power have the same variation tendency with that of the TENG, while the peak power can be achieved at the loading resistor of 30 kΩ. The tunable output voltage/current of the EMG and a relatively small internal resistance difference between that of two generators imply that a great possibility and feasibility on hybridization between the TENG and EMG.

The hybrid nanogenerator is consisted of the TENG and EMG. The TENG harvests rotational energy by coupling of triboelectrification and electrostatic induction. The typical working mechanism is clearly revealed in Figure 2A. An entire charge transfer cycle is formed from to full overlap to sliding out to next sliding in. When the PTFE is sliding out from the Al electrode, to compensate the mismatched tribo-charges, electrons will be driven from ground to the Al by the interfacial electric potential difference. On the contrary, the interfacial potential difference will drive electrons back to ground to fabricate an electrobalance. As a result, the maximal amount of transferred charges corresponds to the smallest interfacial potential difference. As calculated in Figure 2B,C, as the rotator spins relative to the cylinder (i → ii → iii → iv), the potential difference decreases firstly and then increases, while the charge transfer possesses an opposite tendency on the contact interface. The charge transfer between the Al and ground is in accord with the electric potential distribution variation simulated via COMSOL. The proposed model is based on a PTFE strip and an Al plate with the same size as the real device. The triboelectric charge density on the PTFE was assumed to be −10 μC/m². The Al electrode was connected with the ground. As the PTFE strip slides across the Al electrode, the interfacial potential difference shows a variation trend of first decrease and subsequent increase, which is consistent with that of the interfacial potential difference. With regard to the EMG, the essential working mechanism is based on variation of magnetic flux through the coil. The magnetization along Y-axis is 750 kA/m. The constructed mode has a same size as the read device. As sketched in Figure 2D, at the original stage (i), four magnets with the uniform polarity orientation are in a full overlap with coils. At this moment, the magnetic flux through the coils is maximal with no current in the coils. The flux will decline firstly and reach the minimum (ii), then increase gradually, and recover to the initial stage eventually (iii) as the magnets rotate relative to the cylinder (i → ii → iii), which will lead to an induced positive current firstly (i → ii) and subsequently an negative current in the coils (ii → iii). As long as the rotor runs, the continuous electricity can be generated by the hybrid nanogenerator. The TENG and EMG can operate independently without interfering.

To verify the feasibility of hybridization, the output performance of the hybrid device was explored. To narrow the internal resistance difference between the TENG and EMG, the schematic diagram of hybridization is sketched in Figure S1 according to internal resistance variation by coupling of the EMG and transformer. Figure 3A,B show the output voltage and current curves, indicating the open-circuit voltage of about 15 V with the short-circuit current close to 0.1 mA. Similarly, the output voltage improves with the increasing loading resistance, while the maximal output power of about 1.8 mW is achieved at a 20 kΩ loading (Figure 3C). The suitable internal resistance facilitates impedance matching that can deliver higher power delivery. As illuminated in Figure 3D clearly, after being hybridized, the value of output voltage is between that of the TENG and transformed EMG, expanding its application scope. As for rotatory TENGs, the rotation rate has great influence on the output. It can be seen from Figure 3E,F that the larger rotation rate is, the higher the output voltage and current are. At the rotation rate of 500 rpm, the voltage and current can reach 53 V and 0.25 mA, respectively. Compared with the individual TENG and EMG (Figures S2 and S3), the hybrid device realizes a win-win situation between the output voltage and current. To directly express the usability of output power, Figure 3G displays several capacitors can be charged by our hybrid nanogenerator. Even if the capacitor is of 100 μF, the voltage can improved to more than 6 V within 6 seconds. A further investigation shows the hybrid energy cell can charge a 1 mF capacitor to 3 V within 25 seconds (Figure 3H). Compared with other individuals, the shortest duration is achieved by our hybrid nanogenerator, although the EMG assisted with a transformer shows a just passable performance, which further confirms our effective hybridization.

A rotary cylindric triboelectric-electromagnetic hybrid nanogenerator was assembled with a unique configuration, compared with previous literatures. In past reports, some rational integrations of the TENG and EMG in a double-deck sandwiched structure, the rotating-disk-based hybridized structure, double-layered acrylic substrates as the framework of the whole device separated by four springs at the corners, combination of an EMG including the top and bottom layers
and a TENG including the middle layers with the planar structures, and others, have been explored.47,49-53 Compared with previous structures, our frame has a significant improvement by integrating the TENG and EMG in an acrylic frame, which is compact and miniature in configuration. In terms of durability, magnets, coils, and electrodes were anchored on the grooves, leading to that the long-term reliability can be guaranteed. Furthermore, the output performance is different from previously reported devices enormously. In our work, the hybrid nanogenerator is composed of a TENG and EMG, with the output voltage of the TENG is 35 V while that in earlier paper are 17 V approximately, which indicates our TENG has a preferable output before hybridization compared with the previous report.51,52 As for the EMG, it is observed a peak voltage of 7 V and current of 6.5 mA, respectively. The output performance is similar with that of the preceding

FIGURE 2 A. The working mechanism of the TENG in one operation cycle. B. The relationship between the interfacial potential difference/charge transfer and sliding distance. C. The electric potential distribution on the TENG when the PTFE strips slide across the electrodes. D. The schematic diagram of working principle of the EMG induced by magnetic flux variation.
When the TENG and EMG are hybridized with the assistance of transformers, we can acquire an excellent output performance with the open-circuit voltage of about 15 V and the maximal output power of 1.8 mW, showing that the hybrid nanogenerator possesses widespread applications.

The excellent output performance exhibits its possible application in wireless data transmission or self-powered sensing where the hybrid nanogenerator can work as a sustainable power source, as sketched in Figure 4A. The voltage can be up to 13 V at the rotation rate of 150 rpm, leading to two groups of LEDs with opposite polarity lighted up easily (Figure 4B). When the rotation rate changes, the number of generated voltage peaks at a certain period waves will be different, as plotted in Figure 4C. By calculating the number of voltage peaks, Figure 4D shows a self-powered counting system constructed via a Labview platform where the number of peaks can be displayed on the screen. Besides, due to the precise determination of the peak number, the pulse spacing can be calculated. On the other hand, as the rotation rate increases, the time interval between two voltage pulses will be shorted. As depicted in Figure 4E,F, a programmable self-powered timer shows a capacity of precisely timing. At the three different rotation rates (120, 150, and 200 rpm), the self-powered blocktimer indicates a desirable self-clocking ability. The self-powered counting and timing capacity imply a potential in speed detection. Moreover, with assistance of a Li-ion battery, our hybrid device can be used to drive a

**FIGURE 3**  A-C, The output voltage/current and relationship between voltage/power and loading resistance. D, Comparison between output voltages generated by the TENG, transformed EMG and hybrid device. E and F, The dependence of voltage and current on rotation rate. G, The charging curves of capacitors powered by the hybrid generator. H, The charging curves of a 1 mF capacitor powered by different generators
barometer sustainably. As long as the hybrid device works continuously, the barometric signals inside a basketball can be transmitted wirelessly at a certain time interval. A voltage drop arises at every signal transmission, as illustrated in Figure 4G. This is because the smallest working voltage of the pressure sensor is 1.4 V with the corresponding pulse power of about 0.14 mW (the pulse current through the sensor is about 0.1 mA). The Li-ion battery can be charged to 2.4 V easily. At this stage, the pressure sensor can continuously operate nearly 10 seconds effectively. During an 80 seconds charging process, the voltage can be recovered to 2.4 V. Consequently, by the cycle of charging 80 seconds and then operating 10 seconds, the pressure sensor and transmitter system can realize a desirable self-powered operating mode based on the hybrid nanogenerator with the switching between operating and standby mode. The detected pressure data can be extracted remotely. Further than that, our hybrid energy harvester is easily installed at an axle. As sketched in Figure 4H,I, when the wheel is at rotation, the generated electricity is continuously stored in a battery (Figure S4), which then can power a transmitter and pressure sensor system to send tire pressure signals out by switching between operating and standby mode. In this case, the generated electricity by the hybrid device is sufficient for monitoring the tire pressure and sending data out, leading to monitoring tire pressure remotely and wirelessly. The integrated self-powered tire pressure monitor based on a hybrid nanogenerator can operate actively by grabbing rotational energy from axles without using any external power sources, indicating its potential application in active vehicle monitoring.
4 | CONCLUSION

We have demonstrated a cylinder-based hybrid rotary nanogenerator that can grab rotational energy and serve as a sustainable power source for realizing a self-powered tire pressure monitoring system. The hybrid nanogenerator integrated with a transformer can achieve an open-circuit voltage of 16 V at the rotation rate of 150 rpm, with the maximal output power of about 1.8 mW at the loading of 20 kΩ. A self-powered counter and timer were demonstrated based on the hybrid device for potential speed detecting via a programmable software. Further, it has been proved that the hybrid nanogenerator is capable of triggering a transmitter-integrated tire pressure sensor for self-powered monitoring real-time tire pressure that can provide a great benefit to vehicle safety. Our work presents a significant step on TENG-based applications toward automobile engineering and will be widely adopted in intelligence engineering and Internet of Things.

ACKNOWLEDGMENTS

This work is supported by the Scientific and Technological Projects for Distinguished Young Scholars of Sichuan Province (No. 2017JQ0016), Scientific and Technological Innovation Programs of Higher Education Institutions in Shanxi (STIP) (No. 201802028), and Youth Top Talent Program of Shanxi Province (2018).

ORCID

Hulin Zhang https://orcid.org/0000-0003-4899-1491

REFERENCES

1. Fu Y, Ouyang H, Davis RB. Nonlinear dynamics and triboelectric energy harvesting from a three-degree-of-freedom vibro-impact oscillator. Nonlinear Dyn. 2018;92:1985-2004.
2. Dong S, Zhai J, Li JF, Viehland D, Priya S. Multimodal system for harvesting magnetic and mechanical energy. Appl Phys Lett. 2008;93:91.
3. Zeng W, Tao XM, Chen S, Shang S, Chan HLW, Choy SH. Highly durable all-fiber nanogenerator for mechanical energy harvesting. Energy Environ Sci. 2013;6:2631-2638.
4. Wang ZL, Song J. Piezoelectric nanogenerators based on zinc oxide nanowire arrays. Science. 2006;312:242-246.
5. Stark BH, Mitcheson PD, Peng M, Green TC, Yeatman EM, Holmes AS. Converter circuit design, semiconductor device selection and analysis of parasitics for micropower electrostatic generators. IEEE Trans Power Electron. 2006;21:27-37.
6. Sun DM, Wang K, Zhang XJ, Guo YN, Xu Y, Qiu LM. A traveling-wave thermoacoustic electric generator with a variable electric R-C load. Appl Energy. 2013;106:377-382.
7. Berbıyek V, Sodhani J. Towards modelling and design of magnetostrictive electric generators. Comput Struct. 2005;86:307-313.
8. Fan FR, Tian Z-Q, Wang ZL. Flexible triboelectric generator. Nano Energy. 2012;1:328-334.
9. Wang S, Long L, Xie Y, Jing Q, Niu S, Wang ZL. Sliding-triboelectric nanogenerators based on in-plane charge-separation mechanism. Nano Lett. 2013;13:2226-2233.
10. Lin L, Wang S, Xie Y, et al. Segmentally structured disk triboelectric nanogenerator for harvesting rotational mechanical energy. Nano Lett. 2013;13:2916-2923.
11. Niu S, Wang S, Long L, et al. Theoretical study of contact-mode triboelectric nanogenerators as an effective power source. Energy Environ Sci. 2013;6:3576-3583.
12. Yang W, Chen J, Zhu G, et al. Harvesting vibration energy by a triple-cantilever based triboelectric nanogenerator. Nano Res. 2013;6(880-886):11317.
13. Yang W, Chen J, Zhu G, et al. Harvesting energy from the natural vibration of human walking. ACS Nano. 2013;7:11317-11324.
14. Zhu G, Chen J, Liu Y, et al. Linear-grating triboelectric generator based on sliding electrification. Nano Lett. 2013;13:2282-2289.
15. Chen J, Yang J, Guo H, et al. Automatic mode transition enabled robust triboelectric nanogenerators. ACS Nano. 2015;9:12334-12343.
16. Zhang H, Wang J, Xie Y, et al. Self-powered, wireless, remote meteorologic monitoring based on triboelectric nanogenerator operated by scavenging wind energy. ACS Appl Mater Interf. 2016;8:32649-32654.
17. Cao X, Yang Jie Y, Wang N, Wang ZL. Triboelectric nanogenerators driven self-powered electrochemical processes for energy and environmental science. Adv Energy Mater. 2016;6:1600665.
18. Yang J, Chen J, Yang Y, et al. Broadband vibrational energy harvesting based on a triboelectric nanogenerator. Adv Energy Mater. 2014;4:1301322.
19. Wu Y, Jing Q, Chen J, et al. A self-powered angle measurement sensor based on triboelectric nanogenerator. Adv Funct Mater. 2015;25:2166-2174.
20. Zhu G, Bai P, Chen J, Jing Q, Wang ZL. Triboelectric nanogenerators as a new energy technology: from fundamentals, devices, to applications. Nano Energy. 2015;14:126-138.
21. Bai P, Zhu G, Lin ZH, et al. Integrated multilayered triboelectric nanogenerator for harvesting biomechanical energy from human motions. ACS Nano. 2013;7:3713-3719.
22. Niu S, Liu Y, Zhou YS, Wang S, Lin L, Wang ZL. Optimization of triboelectric nanogenerator charging systems for efficient energy harvesting and storage. IEEE Trans Electron Devices. 2015;62:641-647.
23. Cheng G, Wei Z, Fang J, et al. Fabrication of triboelectric nanogenerator with textured surface and its electric output performance. Acta Phys Sin. 2016;65:060201.
24. Chen J, Huang Y, Zhang N, et al. Micro-cable structured textile as an effective power source. Energy. 2013;13:2916-2923.
30. Flatscher M, Dielacher M, Herndl T, et al. A bulk acoustic wave (BAW) based transceiver for an in-tire-pressure monitoring sensor node. IEEE J Solid-State Circuit. 2009;45:167-177.
31. Wei C, Wei Z, Quan W, Xia X, Li X. TPMS (tire-pressure monitoring system) sensors: monolithic integration of surface-micromachined piezoresistive pressure sensor and self-testable accelerometer. Microelectron Eng. 2012;91:167-173.
32. He Z, Hu J, Park BB, Levin MW. Vehicle sensor data-based transportation research: modeling, analysis, and management. J Intell Transp Syst. 2019;23:99-102.
33. Wu W, Cao X, Zou J, et al. Triboelectric nanogenerator boosts smart green tires. Adv Funct Mater. 2019;29:1806331.
34. Seo J, Jhang KY, Lee H, Kim YC. Vibration energy harvesting technology for smart tire monitoring. J Mech Sci Technol. 2019;33:3725-3732.
35. Mendoza-Petit MF, Garcia-Pozuelo D, Diaz V, Olatunbosun O. A strain-based method to estimate tire parameters for intelligent tires under complex maneuvering operations. Sensors. 2019;19:2973.
36. Esmaeili R, Aliniagerdroudbari H, Hashemi SR, et al. A rainbow piezoelectric energy harvesting system for intelligent tire monitoring applications. J Energy Resour Technol-Trans ASME. 2019;141:062007.
37. Lam AYS, Leung YW, Chu X. Autonomous vehicle public transportation system: scheduling and admission control. IEEE Trans Intell Transp Syst. 2015;17:1210-1226.
38. Jo Y, Jung I. Analysis of vehicle detection with WSN-based ultrasonic sensors. Sensors. 2014;14:14050-14069.
39. Hu YF, Xu C, Zhang Y, Lin L, Snyder RL, Wang ZL. A nanogenerator for energy harvesting from a rotating tire and its application as a self-powered pressure/speed sensor. Adv. Mater. 2011;23:4068-4071.
40. Kim H, Tai WC, Parker J, Zuo L. Self-tuning stochastic resonance energy harvesting for rotating systems under modulated noise and its application to smart tires. Mech Syst Signal Proc. 2019;122:769-785.
41. Liu PF, Zhao Q, Yang HL, et al. Numerical study on influence of piezoelectric energy harvester on asphalt pavement structural responses. J Mater Civ Eng. 2019;31:04019008.
42. Naito Y, Uenishi K. Electrostatic MEMS vibration energy harvesters inside of tire treads. Sensors. 2019;19:890.
43. Askari H, Hashemi E, Khajepour A, Khamsee MB, Wang ZL. Tire condition monitoring and intelligent tires using nanogenerators based on piezoelectric, electromagnetic, and triboelectric effects. Adv Mater Technol. 2019;4:1800105.
44. Chen J, Zhu G, Yang W, et al. Harmonic-resonator-based triboelectric nanogenerator as a sustainable power source and a self-powered active vibration sensor. Adv Mater. 2013;25:6094-6099.
45. Zhang C, Tang W, Han C, Fan F, Wang ZL. Theoretical comparison, equivalent transformation, and conjunction operations of electromagnetic induction generator and triboelectric nanogenerator for harvesting mechanical energy. Adv Mater. 2014;26:3580-3591.
46. Wang X, Wang S, Yang Y, Wang ZL. Hybridized electromagnetic–triboelectric nanogenerator for scavenging air-flow energy to sustainably power temperature sensors. ACS Nano. 2015;9:4553-4562.
47. Zhang B, Chen J, Jin L, et al. Rotating-disk-based hybridized electromagnetic-triboelectric nanogenerator for sustainably powering wireless traffic volume sensors. ACS Nano. 2016;10:6241-6247.
48. Hu Y, Yang J, Niu S, Wu W, Wang ZL. Hybridizing triboelectric and electromagnetic induction effects for high-efficient mechanical energy harvesting. ACS Nano. 2014;8:7442-7450.
49. Jin L, Chen J, Zhang B, et al. Self-powered safety helmet based on hybridized nanogenerator for emergency. ACS Nano. 2016;10:7874-7881.
50. Ying Y, Zhang H, Wang J, et al. Hybrid nanogenerators for low frequency vibration energy harvesting and self-powered wireless locating. Mater Res Express. 2018;5:015510.
51. Wang X, Wang SH, Yang Y, Wang ZL. Hybridized electromagnetic-triboelectric nanogenerator for scavenging air-flow energy to sustainably power temperature sensors. ACS Nano. 2015;9:4553-4562.
52. Zhong X, Yang Y, Wang X, Wang ZL. Rotating-disk-based hybridized electromagnetic-triboelectric nanogenerator for scavenging biomechanical energy as a mobile power source. Nano Energy. 2015;13:771-780.
53. Zhang K, Wang X, Yang Y, Wang ZL. Hybridized electromagnetic-triboelectric nanogenerator for scavenging biomechanical energy for sustainably powering wearable electronics. ACS Nano. 2015;9:3521-3529.

SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section.

How to cite this article: He J, Cao S, Zhang H. Cylinder-based hybrid rotary nanogenerator for harvesting rotational energy from axles and self-powered tire pressure monitoring. Energy Sci Eng. 2020;8:291–299. https://doi.org/10.1002/ese3.560