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RAPID COMMUNICATION

Self-powered triboelectric velocity sensor for dual-mode sensing of rectified linear and rotary motions

Qingshen Jing[a,b], Guang Zhu[b,c], Wenzhuo Wu[b], Peng Bai[b], Yannan Xie[b], Ray P.S. Han[a,*], Zhong Lin Wang[b,c,]**

[a]*Department of Materials Science and Engineering, Peking University, Beijing 100871, China*
[b]*School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0245, United States*
[c]*Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing, China*

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Abstract
A practical self-powered velocity sensor based on the principles of a triboelectric generator for either rectified linear or rotary motion is presented. The effort represents the first successful attempt in integrating a triboelectric generator into a commercial digital circuit for the dual-mode speed sensing. Employing alternating Kapton-copper strips arranged in a spiral configuration wrapped on the inner and outer surfaces of two concentric cylinders, voltage assays for linear and rotary motions can be measured without the need for an external power source. The triboelectric generated output signals when integrated with a digital circuit and a microcontroller unit can be directly processed into remarkably stable, macro-scale output signals for measurements of $(0.1-0.6)\ \mathrm{ms}^{-1} \pm 0.5\%$ for linear velocities and $(300-700)\ \mathrm{rpm} \pm 0.9\%$ for rotary velocities. We have also discussed the measuring sensitivities and limitations of our device in the paper. We believe our pioneering demonstration of the applied triboelectric technology will have a huge impact in the industrial commercialization of self-powered devices and sensors.

Introduction

Velocity measurements are essential in many modern industrial applications in automation, transportation, robotics,

*Corresponding author.
**Corresponding author at: School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0245, United States.
E-mail addresses: ray-han@pku.edu.cn (R.P.S. Han), zlwang@gatech.edu (Z.L. Wang).

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etc. The well-developed methods for velocity measurements include technologies based on potentiometers [1], magneto resistive sensing [2], magnetic field sensors [3], optical encoders [4], capacitive sensing [1], piezoelectric sensors [5-7], etc. Most of these sensing technologies suffer from a shortcoming: they require a power supply to sense the mechanical motion. Such sensors can be classified as passive because they cannot actively detect a change in the environment without being driven by electricity. Even for some active sensors that are designed to initially generate electrical signals [5-8], the outputs are rather small and they need a sophisticated equipment for measurement, which may prohibit their applications to some extent. The invention of the first triboelectric generator (TEG) [9] that uses the tribo-electrification and electrostatic induction effects to generate electrical output allows the technology to be applied in the harvesting of the mechanical energy [10-12] and in self-powered sensor fields such as magnetic field sensor [13], position sensors [14], acoustic sensors [15] and chemical sensors [16,17]. Theoretical studies [18] showed strong regular pattern and stability in the TEG outputs for a cost-effective mechanical sensing. Based on the theory, various types of motion sensors have been developed [19-22]. Recently, a one-dimensional nano-scale motion sensor was developed to detect nanometer-scale movements [23]. The work represents the first triboelectric-related research on velocity/position sensing in a one-dimensional array; however, the detected output voltage/current signals were micro-scale in magnitude, and thus, too small for practical applications.

We report on a practical self-powered sensor for velocity measurements for either linear or rotary motion. The effort represents the first successful attempt in integrating a triboelectric generator with a comparator-microcontroller unit (MCU) into a commercial digital circuit for the dual mode velocity sensing. Patterned with alternating Kapton-copper strips arranged in a 45°-helix on both sides of the contact surface and packed in a case-encapsulated structure, the generator produced remarkably stable, macro-scale output signals for measurements of $(0.1-0.6)$ $\mathrm{ms}^{-1} \pm 0.5\%$ for linear velocities and $(300-700)$ rpm$\pm 0.9\%$ for rotary velocities. Our velocity sensor demonstrates the technical feasibility and commercial potential of triboelectricity for self-powered devices and sensors.

Results and discussions

The schematic and actual structures of the velocity sensing triboelectric generator (vsTEG) are shown respectively, in Figure 1a1 and a2 as consisting of a pair of coaxially-placed cylindrical tubes. The two tubes move relative to each other either in a rotational (Figure 1a3) or sliding (Figure 1a4) motion. The mechanism of the velocity sensing capability can be explained as coming from the induced triboelectric charge transfer between the interfaces and its subsequent lateral polarization as driven by the relative motion. To fabricate the interfaces, a polyimide film (Kapton®) was used not only as a durable supporting substrate but even more importantly, as a high-performance electrification material [24] for generating the triboelectric charges during the sliding motion with the copper electrodes. On either side of the Kapton film, copper stripes are deposited with a linear pitch of 8 mm. Hence, the electrode stripes on the 2 sides form a linear shift of half a pitch giving rise to an alternating pattern with one another (Figure 1b). The Kapton film is then carefully wrapped over the acrylic cylinder with the strip direction at a 45° screw-angle with the cylinder axis (Figure 1a1 and a2). A second Kapton film with the same electrode pattern is encased in the foam sleeve for producing the relative motion (Figure 1a1). It should also be mentioned that the width of each copper strip (≈ 4 mm) is significantly larger than its thickness (≈ 1 μm). As a result, the inner and outer surfaces will not encounter the problem of “non-contacting 2 plates” during the device operation. An inner electrode (IE) is formed by stringing together the copper stripes at the 2 contact surfaces via bus electrodes; likewise, an outer electrode (OE) is formed by those on the other side of the Kapton film (Figure 1c). The output signal is read from the voltage over load R in the connected IE and OE (Figure 1c).

The vsTEG begins to actively generate output signals for velocity sensing when relative linear or rotary motion between the 2 interfaces occurs. The electricity generation mechanism of the vsTEG is illustrated in Figure 2a. The triboelectric charge transfer due to the Kapton and copper being brought into contact causes the electrons to be injected between the 2 dissimilar metals generating current flow between the IE and OE (see Figure 2a1-a5). Both the motion and electric signal complete their cycles at the state in Figure 2a5 and return back to the starting cycle state in Figure 2a1. Since the generated electric signal cycle stays consistently in sync with the driving mechanical (or motion) cycle, the retrieved velocity information is both stable and reliable.

The electric signals generated by the triboelectric charge transfer due to the dynamic mismatch between the strips exist as long as there is a component of the relative velocity that is perpendiculars to the strip directions. To further understand this mechanism, open-circuit voltages (V_{oc}) as well as charge accumulations (Q_{ac}) under the short-circuit condition between the IE and the OE are studied via finite element (FE) simulations (see details in *Experiments*) in a 2-dimentional space. The V_{oc} and Q_{ac} are assumed to be functions of spatial positions and are calculated by placing a smaller layer of the treated Kapton film over a larger layer at different positions (Figure 2b) with the strip direction forming a 45° angle to both the x- and y-axes. Both V_{oc} and Q_{ac} showed a “wavy” shape distribution that is consistent with the structural variation of the strips (Figure 2c and d). FE simulations confirmed that a relative motion with a velocity component that is perpendiculars to the 45° direction generates a periodic output. Denoting θ as the angle between the direction of motion and the x-axis (Figure 2e), the cycle time of V_{oc}, T can be obtained from:

$$T = \frac{w_{pitch}}{v_{sliding}\ \cos(45^\circ - \theta)} \tag{1}$$

where w_{pitch} refers to the pitch distance and $v_{sliding}$ to the sliding velocity along the given θ direction. Output signal variations that correspond to θ ($0 \le \theta \le 90^\circ$) for our dual-use vsTEG design with the inner cylinder moving either linearly with $\theta = 90^\circ$ or in a rotary motion with $\theta = 0^\circ$ are studied in supporting information (SI) S1. To characterize the