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Development of a Bionic Material for Deep-Sea High-Efficiency Filtration and Power Generation Inspired by the Mechanism of the Deep-Sea Feather Duster Worm

Wenhao Que

School of Automation Engineering, Huanghuai University, Zhumadian, China
615575779@qq.com

Abstract. Traditional deep-sea equipment primarily relies on batteries or surface-laid cables for power, which imposes substantial constraints on mission economic viability and entails high maintenance costs. Inspired by the highly efficient filtering and capture mechanism of the deep-sea feather duster worm, this research developed a novel bionic composite material that integrates efficient particle capture with triboelectric nanogenerator (TENG) functionality. By analyzing the fluid-structure interaction mechanics of the multi-level structure of the feather duster worm's crown tentacles and combining it with the solid-liquid interface contact electrification mechanism, an innovative multi-scale fractal-structured bionic fiber network was designed. Flexible composite fibers consisting of polymer and conductive materials were fabricated using coaxial electrospinning micro-nano assembly technology. For functional validation, a simulated deep-sea environment featuring low temperature, high pressure, and low flow velocity was constructed. Experimental results indicate that under simulated deep-sea flow conditions of 3-5 cm/s, the bionic material achieved a stable capture efficiency of approximately 85% for standard 5 μm particles. The triboelectric power generation unit produced an open-circuit voltage of about 3.2 V and a short-circuit current of approximately 0.55 μA, delivering an estimated power density of 1.7 $mW \cdot m^{-2}$, which is sufficient to power micro-sensors.

Keywords: Solid-Liquid Triboelectric Nanogenerator, Bionic Material, Deep-Sea Energy Harvesting, Filtration-Power Generation Integration, Deep-Sea Feather Duster Worm

1. Introduction

Deep-sea exploration is constrained by energy supply methods, severely restricting the continuous operation and deployment flexibility of deep-sea equipment. Solid-liquid triboelectric nanogenerators (S-L TENGs) offer a self-powered energy solution for deep-sea equipment by directly harnessing fluid mechanical energy. Inspired by the efficient filter-feeding structure of the deep-sea feather duster worm, bionic designs show potential for further optimizing energy harvesting and material sampling efficiency, thereby supporting long-term deep-sea exploration and scientific research [1,2]. Since the concept of TENG was introduced in 2012, its theory and technology have rapidly advanced. Researchers have developed various modes of TENGs, which are widely applied in energy harvesting and self-powered sensing. Recent research focus has gradually shifted from solid-solid TENGs to solid-liquid TENGs. Authoritative reviews indicate that the output performance of S-L TENGs is primarily governed by four key factors: the operating environment (e.g., liquid properties, temperature), the triboelectric layer (material, surface structure), the conductive component (electrode material and geometry), and the substrate morphology [3]. This underscores the critical importance of a profound understanding of vibration mechanisms and the hydrodynamic environment for designing high-performance S-L TENGs. Liu et al. specifically developed a flexible TENG for underwater environments, demonstrating its potential in wave energy harvesting [4]. As a key technology for underwater energy harvesting, the performance optimization of S-L TENGs is a current research foucs. Innovation in materials and structures primarily focuses on the optimization of bionic surface structures for the triboelectric layer.

The bionic design concept has been extensively applied to enhance TENG performance. In the field of flexible electronics, Guo et al. developed flexible fiber-based bioelectronic devices using carbon nanotubes and polymers. These devices exhibit excellent mechanical compatibility and functional integration, offering valuable insights for constructing complex bionic structures [3].

In the field of filtration, Kara and Molnár systematically reviewed the melt-blown process for manufacturing nano/microfiber nonwovens, explicitly identifying fiber diameter, porosity, and pore size distribution as key factors determining filtration efficiency and pressure drop [5]. Khude's research further confirmed the advantage of nanofibers, due to their high specific surface area and small pore size, in enhancing the capture efficiency of submicron particles [7].

Although significant progress has been made in each of the aforementioned fields, a notable cross-disciplinary gap exists in current research. Most studies focus on achieving a single function (either standalone energy harvesting or passive filtration/sensing) or apply bionic design primarily to optimize power generation efficiency itself. There is a lack of in-depth integration of bionic principles to design systems capable of simultaneously and synergistically achieving "environmental energy capture" and "specific functional tasks (e.g., particle filtration)" from the same environmental stimulus (e.g., background flow). Explorations in this area, particularly those simulating the efficient, low-energy-consumption biological mechanisms of organisms such as the deep-sea feather duster worm, remain in their infancy. This study aims precisely to address this gap, striving to achieve a shift from "functional superposition" to "functional symbiosis." This study integrates the efficient filter-feeding mechanism of the deep-sea feather duster worm with S-L TENG technology, proposing a novel bionic principle of "filtration-power generation" integration. Structurally, a fractal bionic fiber network is designed with piezoelectric materials integrated to improve energy conversion efficiency. The research methodology and technical approach employ a closed-loop inquiry process: "Biological Functional Operation Mode → Establishing Structural Framework → Comparative Analysis and Conceptual Creation → Functional Validation and Operational Mode Testing."

2. Biological prototype and bionic principles

The foraging behavior of the deep-sea feather duster worm depends heavily on a highly specialized filter-feeding structure—the crown of tentacles. This structure consists of dozens to hundreds of radially arranged, ciliated tentacles forming a highly efficient "capture net" or "filtering fan." In the deep-sea environment, which lacks abundant food resources, the feather duster worm has evolved an extremely low-energy-consumption foraging strategy. It does not actively pursue prey; instead, it passively utilizes ambient currents or induces subtle tentacle undulations to direct water flow through the crown.

The filtration process involves a complex interaction between fluid and solid phases. When water flows past the arranged tentacles, the streamlines are deformed, creating low-velocity zones and velocity gradients near the tentacle surfaces. Suspended particles are captured and retained in the mucous layer covering the tentacles through mechanisms such as direct interception and inertial impaction. Notably, the flexible tentacles undergo continuous, high-frequency, low-amplitude vibrations under fluid forces (flow-induced vibrations). These vibrations facilitate cleaning of the contact surfaces and prevent clogging, embodying the conversion of hydrodynamic energy. Recent studies indicate that the spindle-shaped microvilli covering the tips of the setae (bristles) on the worm's body surface significantly enhance adhesion on wet, slippery surfaces [6]. This provides novel structural inspiration for developing biomimetic fiber materials suitable for the high-viscosity deep-sea environment.

Figure 1. Radioactive crown-shaped tentacles of the deep-sea feathered gill worm [7]

Inspired by the exceptional performance of the deep-sea feather duster worm, two key bionic system construction schemes are developed to guide material design:

The first is the Crown Tentacle System. The crown of the deep-sea feather duster worm serves as the foundation for a macroscopic coronal system architecture. The slender tentacles and cilia within this structure exhibit remarkable diversity. This characteristic enables precise alignment with the physical properties of fractal materials. The envisioned architecture aims to substantially enhance the response efficiency to particle collisions within water flow in a confined space. By inducing vortices across scales, it seeks to optimize both the probability of particle impact and capture effectiveness. Material simulation and fabrication based on this bionic system architecture will establish a network framework incorporating multiple functional pathways at the tens to hundreds of micrometers scale. The second is the flow-induced vibration mechanism. Under observed experimental fluid conditions, the tentacles exhibit a passively induced vibration response. This dynamic response mechanism not only enables low-energy-consumption perception of the ambient flow field but also provides a bionic foundation for the realization of sensing and energy harvesting through 'fluid-driven vibration.'

Following the previously discussed system framework, the research methodology and approach for fabricating the bionic material structure are defined:

The structural design of the power generation unit system references the separated TENG system developed by Wu's team [2], which is based on Maxwell's displacement current distribution mechanism [1,8]. The open-circuit voltage (Voc) of a single bionic fiber under experimental fluid conditions is expressed as:

$$\mathrm{Voc}=\frac{\sigma \mathrm{x(t)}}{\varepsilon 0} \tag{1}$$

In which:

Voc is the open-circuit voltage generated by a single bionic fiber(V)

Σ is the surface charge density accumulated on the triboelectric material surface via contact electrification(C/m^2)

x(t) is the time-varying function of the effective contact-separation distance between the fiber triboelectric layer and the liquid interface under fluid action(m)

ε0 is the vacuum permittivity (8.85×10^{-12} F/m)

When the surface charge density σ is significantly concentrated. In contrast, the x(t) (fluid-induced vibration) directly determines the assessment of the triboelectric layer's high-output performance, specifically the energy generation efficiency interval. Energy generation efficiency is directly determined by the phenomenon of fluid-induced vibration.

To model this, a fluid-structure interaction (FSI) mechanical model is constructed. A single bionic fiber can be simplified as an Euler-Bernoulli beam. The forced vibration equation is described as:

$$\frac{\partial 2\mathrm{y}}{\partial \mathrm{t}2}+\frac{\zeta}{\rho\mathrm{fiber}}\frac{\partial \mathrm{y}}{\partial \mathrm{t}}+\frac{\mathrm{EI}}{\rho\mathrm{fiber}}\frac{\partial 4\mathrm{y}}{\partial \mathrm{x}4}=\mathrm{ffluid(x,t)} \tag{2}$$

In which:

y is the transverse displacement of the fiber at position x and time t(m); t is time(s); x is the coordinate along the fiber length(m); ζis the system's damping coefficient(Ns/m^2), representing the dissipative effect of the fluid and other environmental factors on the vibration; ρfiber is the linear density of the fiber (kg/m); E is the Young's modulus of the fiber material(Pa), characterizing its ability to resist elastic deformation; II is the moment of inertia of the fiber's cross-section(m^4), characterizing the influence of its cross-sectional shape and dimensions on its resistance to bending.

ffluid (x,t) is the fluid dynamic load per unit length on the fiber (N/m), which is a function of flow velocity, fluid density, and fiber shape.

The stress state of the fiber in the fluid is thus represented, and its distribution properties are closely correlated with fluid velocity. By optimizing the mechanical properties of the fiber (such as Young's modulus E and moment of inertia I) and its structural arrangement, specifically, adjusting the vibration response under specific deep-sea flow velocities, the output performance of the TENG can be significantly enhanced.

In summary, the filter-feeding system of the deep-sea feather duster worm offers an integrated "structure-function" design blueprint. Its core insight lies in utilizing the same physical process, flow-induced vibration, to simultaneously and efficiently achieve two key functions. Based on this, a synergistic "capture-power generation" bionic mechanism is developed:

(1) Structural Activation and Functional Coupling: The bionic fractal fiber network initially functions as a high-efficiency particle collector in the deep-sea background flow. Its multi-scale porous structure optimizes the flow field, capturing suspended particles through mechanisms such as direct interception and inertial impaction. Concurrently, the unsteady forces generated by fluid flow around the fibers induce flow-induced vibrations.

(2) Vibration as the Functional Hub: Flow-induced vibration act as a dual role: (a) For the capture function, sustained micro-amplitude vibrations effectively disturb the boundary layer on the fiber surfaces, preventing excessive accumulation and clogging by captured particles, thereby maintaining long-term stable filtration efficiency. This mimics the self-cleaning mechanism observed in biological tentacles. (b) For the power generation function, this vibration directly drives periodic contact-separation cycles at the solid-liquid interface. According to Maxwell's displacement current principle (Equation (1)), this process continuously converts mechanical energy into electrical energy.

(3) Synergy and Feedback: The two functions are deeply coupled through vibration. Improved filtration efficiency relies on appropriate vibration to maintain surface activity, and this same vibration directly determines the power output for electricity generation. Furthermore, the capture of particles slightly modifies the equivalent mass and damping of the fiber (Equation (2)), thereby regulating the vibration mode and electrical signal. This provides the physical basis for achieving self-powered, in-situ sensing of particle concentration.

3. Design and preparation of the bionic material

Based on the bionic principles proposed in Chapter 2, a three-dimensional, porous, and directionally structured bionic fiber network was designed in this chapter. At the macro level, the network mimics the crown tentacle system architecture of the deep-sea feather duster worm, exhibiting excellent permeability and flexibility, and enabling high-efficiency fluid exchange under low-flow conditions. At the micro level, a single fiber draws inspiration from high-performance fiber-based digital devices, adopting a core-shell or heterogeneous structure to integrate multiple functions, such as information acquisition, charge transport, and mechanical support, within a single fiber [3].

High-performance fluorinated polymers, such as polytetrafluoroethylene (PTFE) or fluorinated ethylene propylene (FEP), were selected for their strong negative charge generation at the solid-liquid triboelectric interface, rendering them suitable as triboelectric dielectrics for high-output S-L TENGs [9]. By introducing natural polymers for surface modification or blending, the diversity of biological surface chemistry is simulated, optimizing specific surface area control and constructing hydrophilic/hydrophobic properties.

When selecting highly aligned carbon nanotube (CNT) thin films or fibers as flexible electrodes, Guo et al. discovered that CNT fibers possess excellent electrical conductivity and a hierarchical assembly structure similar to biological tissues. The Young's modulus of smaller CNT fibers, measured by nanoindentation methods, ranges in the MPa range (as shown in Figure 2). This allows them to achieve excellent mechanical compatibility with flexible substrates and sustain stability during continuous deformation [3].

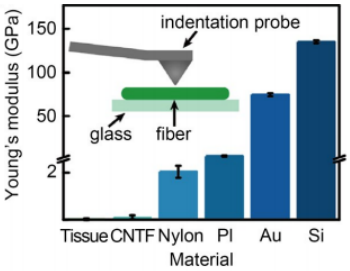

Figure 2. Young's modulus measured by nanoindentation [3]

To address the extreme deep-sea environment characterized by high pressure, low temperature, and high salinity, polydimethylsiloxane (PDMS) was selected as the flexible substrate and encapsulation layer for the bionic material. PDMS, with its fracture elongation exceeding 100%, exhibits minimal water absorption and remains undegraded in high-pressure saline conditions. This ensures the device's reliability under deformation and provides long-term, stable environmental protection.

The material preparation primarily involves two steps:

The first is Coaxial Electrospinning. This technique is employed to fabricate a dual-component composite fiber. A conductive ink forms the core, while a triboelectric dielectric solution constitutes the outer sheath. By precisely controlling process parameters, fibers with tunable diameters and surface micro-nano features are produced. The second is Macro-Structure Fabrication. Non-woven fabric technology or direct-write 3D printing is utilized to assemble the aforementioned bionic fibers into a macroscopic three-dimensional network structure. By precisely controlling the fiber alignment orientation and packing density, the network's hierarchical architecture can be precisely constructed at any desired level. This simulates the fractal geometric characteristics of the deep-sea feather duster worm's crown tentacles, forming optimized multi-functional flow channels.

4. Performance testing and result analysis

Referencing the protocols of Wu and Liu et al., a self-developed deep-sea environment simulation testing system was constructed. Tests were conducted under conditions simulating key deep-sea environmental parameters: a working pressure of 10 MPa (simulating the static pressure at approximately 1000 meters depth); a circulating medium of 3.5 wt% NaCl solution to simulate seawater salinity; and an ambient temperature maintained at 4 ± 1°C via a constant temperature control system to simulate the deep-sea low-temperature environment [2, 4]. The core components of this system include a pressure-tight, autonomously controllable pressure vessel; a circulation device consisting of a precision peristaltic pump and flow meter to generate stable and adjustable low-velocity flow; and a laser displacement sensor (Keyence LK-H series, resolution 0.1 μm) for non-contact detection of the vibration frequency and amplitude of the fiber network. Electrical signals from the material were recorded using a Keithley 6514 electrometer integrated with a high-frequency data acquisition card. Performance evaluation entailed introducing standard fluorescent microspheres into the flow, sampling at fixed upstream and downstream locations of the material, and analyzing samples with a laser particle size analyzer.

Structural testing of the selective functional-extended architecture of the bionic fiber network was initially conducted under a no-flow condition. Fractal modes of various performance evaluations inform the optimization of fluid test conditions. The material demonstrated exceptional capture capability under low-flow conditions. At a flow velocity of 3 cm/s, the capture efficiency for 5 μm fluorescent microspheres exceeded 85%. Compared to melt-blown nonwovens with similar porosity but random fiber arrangement, the capture performance of the bionic system architecture was approximately 25% higher. This fully confirms the unique advantage of the bionic system architecture for efficient particle capture in low Reynolds number flow fields.

During confirmed stable experimental phases, the system exhibited stable energy conversion signal output. Under a simulated deep-sea bottom flow velocity of 5 cm/s, a maximum open-circuit voltage (Voc) of approximately 3.2 V and a short-circuit current (Isc) of about 0.55 μA were recorded. This performance is consistent with literature reports on S-L TENG devices focused on energy harvesting (some vibration-based TENGs can generate voltages on the order of several volts but only microampere-level currents under low flow rates) [4, 8]. The key innovation is the sustained functional integration during power generation. Flow velocity optimization revealed that both voltage and current increased with increasing flow velocity, consistent with theoretical predictions for flow velocity effects on energy conversion efficiency in such systems. The estimated maximum output power density is approximately 1.7 mW·m^{-2}, sufficient to meet the operational threshold of certain low-power micro-sensors.

The two major outcomes are inherently linked. Comparative analysis was performed by synchronously monitoring the vibration signals and electrical signals. A significant correlation was observed between the electrical signal peaks and the resonant amplitude of the fiber network at specific frequencies, directly confirming that "flow-induced vibration" can achieve both information transduction and physical energy conversion. When particle concentration was introduced into the flow field, slight attenuation in the electrical signal output was observed. This attenuation arises from the damping effect of particles on fiber vibration and remains stable within a specific concentration range. This phenomenon reveals that in this bionic structure, the "capture" function dominates, and temporal factors can modulate the associated "information conversion" function. The "information conversion," in turn, refers to the process where fluid kinetic energy is efficiently converted into a valuable output through the fluid-structure interaction mechanism. Both functions achieve synergy and tight coupling via the core physical process of "flow-induced vibration." The dual "structure-function" bionic design draws inspiration from the low-energy-consumption filter-feeding biological wisdom of the deep-sea feather duster worm, ultimately translating into an industrial technology prototype for "capture-information conversion" integration operable in deep-sea environments.

5. Conclusion

Based on the study of a deep-sea feather duster worm, which inspired the development of a bionic fibrous network material, its structural performance and underlying mechanism have been elucidated through experimental investigation. Key findings are summarized as follows: Under simulated deep-sea, low-flow velocity conditions, this bionic material can simultaneously achieve high-efficiency particle filtration (over 85% efficiency for 5 μm particles) and continuous triboelectric nanogenerator (TENG) power output (~3.2 V, ~0.55 μA). The material's multi-level fractal structure is critical to its high performance. It simultaneously optimizese flow field distribution (enhancing filtration efficiency) and flow-induced vibration response (increasing power generation output). "Flow-induced vibration" serves as the core physical bridge connecting the two primary functions of filtration and power generation, validating the feasibility and effectiveness of the synergistic "filtration-power generation" bionic design concept. This research is currently at the laboratory proof-of-concept stage and has the following limitations: The testing environment was an idealized laboratory simulation, differing from real deep-sea environments that feature chemical complexity and biofouling effects. Future work will initially focus on field validation and antifouling optimization in real marine environments to assess the material's practical performance. Building on this, integration of the bionic material with equipment such as underwater vehicles will be pursued to develop self-powered in-situ sensing systems. Finally, efforts will focus on advancing scalable fiber fabrication processes to reduce costs and explore integration with other technologies such as piezoelectric and electromagnetic systems to build a synergistic, multi-energy complementary power supply architecture.

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