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Piezoresistive foam sensor arrays for marine applications

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ABSTRACT

Spatially-dense pressure measurements are needed on curved surfaces in marine environments to provide marine vehicles with the detailed, real-time measurements of the near-field flow necessary to improve performance through flow control. To address this challenge, a waterproof and conformal pressure sensor array comprising carbon black-doped-silicone closed-cell foam (CBPDMS foam) was developed for use in marine applications. The response of the CBPDMS foam sensor arrays was characterized underwater using periodic hydrodynamic pressure stimuli from vertical plunging and surface water waves, from which a piecewise polynomial calibration was developed to describe the sensor response. Inspired by the distributed pressure and velocity sensing capabilities of the fish lateral line, the CBPDMS foam sensor arrays have significant advantages over existing commercial sensors for distributed flow reconstruction and control. Experimental results have shown the sensor arrays to have sensitivity underwater on the order of 5 Pa, dynamic range of 50–500 Pa; are contained in a waterproof and completely flexible package, and have material cost less than $10 per sensor.

1. Introduction

Operating in the marine environment places unique challenges on unmanned systems that require novel approaches to sensing and control. Marine vehicle performance is largely influenced by interactions with the flow around their hull, both self-generated and environmentally-driven. To improve performance through flow control, a detailed, real-time measurement of the near-field flow is necessary, yet such sensing capability is presently unavailable. In nature, fish have overcome this sensory deficit by utilizing feedback from the pressure and velocity sensing capabilities of the lateral line sensory organ. When considering the ability of fish to thrive in the inhospitable marine environment, achieving even a portion of their capabilities with engineering systems would have tremendous benefits to oceanographic research, marine vehicle performance, and undersea exploration. To address the challenges associated with obtaining spatially-dense pressure measurements on curved surfaces in marine environments, a new waterproof and conformal pressure sensor array was developed based on a closed-cell piezoresistive foam comprising carbon black-doped-silicone composite (CBPDMS foam).

1.1. A biological solution: the lateral line

Solutions to complex engineering problems can often be found by looking to nature for inspiration, especially when considering the marine environment which is inhospitable to humans, but contains an incredible degree of bio-diversity. The ability of fish to navigate the undersea world at high speeds and in close proximity to obstacles and other individuals is particularly attractive to ocean engineers seeking to enhance the performance of marine vehicles. The lateral line system found in all species of fish and some amphibians is a hair-cell based mechanosensory organ comprising two primary subsystems: superficial neuromasts and canal neuromasts. Superficial neuromasts are located on the surface of the skin and are generally considered as viscous-drag based velocity sensors [2,3], while the trunk canal subsystem is stimulated by pressure gradients between an array of pores in the animal's skin, acting in a similar fashion to a distributed network of differential pressure sensors [4]. The utilization of distributed pressure measurements as a hydrodynamic feedback mechanism in fish is a primary motivator for the development of pressure sensing technologies for use in marine environments.

Abbreviation: CB, carbon black; PDMS, polydimethylsiloxane; CBPDMS, carbon black-PDMS composite; Ag-CBPDMS, silver-carbon black-PDMS composite.

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2. Bringing lateral line inspired capabilities to marine vehicles

In order to achieve the lateral line mediated capabilities observed in fish with marine vehicles, advancements are needed in the characterization and utilization of near-body hydrodynamic pressure signals, as well as in the development of bio-inspired distributed sensor arrays. To elucidate the design guidelines for a distributed hydrodynamic pressure sensor array, a series of towing tank and field experiments were conducted using arrays of commercially available pressure sensors. Experiments with an instrumented model sailboat hull of length $L = 1$ m were conducted in the MIT towing tank [5]. An array of 10 Honeywell 19 mm series pressure sensors were connected to taps along the length of the model's hull, and it was found that the pressure measurements could be used to accurately estimate the hull's angle of attack. Similarly, Honeywell 19 mm pressure sensors were utilized to study the formation and shedding of leading edge vortices from a hydrofoil towed at large angles of attack [6].

The utility of near-body flow sensing on a surface vehicle was investigated experimentally using an unmanned kayak vehicle equipped with an array of 20 Honeywell SPT series pressure sensors mounted inside the vehicle, necessitating the drilling of holes through the hull to access the flow [7]. It was found that the vehicle dynamics in pitch and roll were measurable by the pressure sensor array, as well as the initiation of vehicle maneuvers due to a characteristic pressure signature consistent with added mass effects during unsteady vehicle motions. The magnitude and frequency of dynamic pressure signals measured during these experiments, and analysis of the sensor spacing on the foil and hull surfaces, lead to the development of design guidelines for distributed pressure sensor arrays given in Section 2.1.

2.1. Guidelines for hydrodynamic pressure sensor arrays

In general, the sensors used in the studies outlined in Section 2 were rigid and too large for surface mounted applications, and were not designed for prolonged exposure to moisture. Based on the results of these studies, the attributes of a pressure sensor array designed specifically for marine use were developed as follows.

Flexibility	Pressure sensor arrays to be surface mounted on curved surfaces with radius of curvature ~5–10 cm, consistent with unmanned vehicle hulls [5–7].
Form factor	Sensor spacing should be less than 5 cm for vehicles on the 1–3 m scale. Sensor thickness should be < 5 mm to avoid vortex shedding [4–6].
Robustness	Sensor arrays are meant for sustained underwater or exposed operation and may be subject to impacts.
Dynamic range	For marine vehicles of length ~1–3 m, dynamic pressure stimuli range from ~10–400 Pa [4–7].
Sensitivity	For marine vehicles of length ~1–3 m, sensitivity of ~10 Pa is desired to characterize hydrodynamic stimuli [4–7].
Cost	Sensor cost should be reduced from ~$100 per sensor to ~$10 per sensor [7].

2.2. Doped-polymer 'smart-skins' for marine applications

Based on the operational requirements for use in distributed pressure sensing on marine vehicles, doped polymer 'smart-skin' arrays offer the best combination of performance characteristics for marine use. Doped polymers allow for the development of a completely waterproof, stretchable, and flexible sensor array through the careful selection of bulk matrix material and conductive dopant. The flexibility, robustness, and resistance to moisture of bulk matrix materials like PDMS (silicone) make doped composites well suited for prolonged environmental exposure while surface mounted on marine vehicle hulls. Additionally, controlling the material properties of the bulk matrix through the introduction of porosity has been shown to increase sensitivity in carbon black-PDMS composites, allowing for piezoresistive composites to be optimized for pressure ranges consistent with hydrodynamic stimulus [8]. Finally, doped polymers make use of cheap and easy to work with component materials, allowing for the scaling of distributed pressure sensor arrays to spatially-dense applications.

3. Carbon black-PDMS composite sensor development

Carbon black-PDMS foam pressure sensor arrays rely on the piezoresistivity, or variation in resistance with strain, of carbon black doped PDMS (silicone) to provide an indirect measurement of pressure stimulus. Carbon black-PDMS (CBPDMS) composite has been studied as an active material for pressure and shear sensors due to its low Young's modulus, ease of fabrication, and low cost [9–13]. Each component composite in the sensor array utilizes PDMS as the matrix material, ensuring strong bonding between sensor components while retaining overall array flexibility. By varying the carbon black doping and Young's modulus between sections of the sensor array, a linear four by one array of sensor channels was created here. Sensing elements were fabricated using a closed-cell CBPDMS foam (Section 4.1.3) with a low Young's modulus and carbon black concentration near the percolation threshold to enhance piezoresistivity and improve the sensitivity of the array to hydrodynamic stimuli. Electrodes were fabricated using a silver-carbon black-PDMS (Ag-CBPDMS) composite with a high mass fraction of silver to ensure high conductance and low piezoresistivity compared to the active foam material, as discussed in Section 4.1.2.

3.1. Models of CBPDMS piezoresistivity

Above a mass fraction of carbon black known as the percolation threshold, carbon black doped PDMS forms a conductive composite. When the percolation threshold is reached, continuous chains of carbon black particles create conductive pathways through the PDMS bulk material; while below the percolation threshold, CBPDMS composite behaves like an insulator. The piezoresistive behavior of CBPDMS relies on the formation and breakdown of these conductive chains as the PDMS matrix material is deformed due to external stimulus.

The resistance change of CBPDMS composite when subjected to an external pressure stimulus has been primarily described using two models, the compressible and incompressible models [12]. Both piezoresistive effects have been observed in CBPDMS composites, and the relationship between resistance and strain is highly dependent on the filler material, the type of polymer matrix, and the nature of the loading [12]. For the CBPDMS foam pressure sensor array using four-point probe measurements and responding to isotropic hydrodynamic stimuli, the resistance change was found to be consistent with the compressible model.

The compressible model of CBPMS piezoresistivity states that as the PDMS matrix is compressed due to external pressure stimulus, the volume fraction of CB particles within the composite is increased, allowing for the formation of new continuous conductive pathways and decreasing the resistance of the composite [12,14,15]. When the external pressure stimulus on the composite is decreased, the material relaxes, and the newly formed conductive