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A MEMS Shear Stress Sensor for Turbulence Measurements

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This paper presents the development of a microelectromechanical systems (MEMS)-based piezoresistive shear stress sensor for the direct, quantitative measurement of time-resolved, fluctuating skin friction. The sensor structure integrates laterally-implanted diffused piezoresistors into the sidewall of the sensor tethers for detecting the floating element deflection via a strain-induced resistance change. The sensor was optimally designed using a nonlinear electromechanical model. Preliminary experimental characterization indicates a sensitivity of $4.24\ \mu V/Pa$ and a noise floor of $48.2\ nV/\sqrt{Hz}$ (for a $1\ Hz$ bin centered at $1\ kHz$) for a bias voltage of $1.5\ \mathrm{V}$. The tested device is linear up to the maximum testing range of $2\ Pa$ and possesses a flat dynamic response up to the frequency testing limit of $6.7\ kHz$.

I. Introduction

The quantification of wall shear stress is important in a variety of engineering applications, specifically in development of aerospace and naval vehicles. The vehicles of interest can operate at low Reynolds numbers (Re) (unmanned air vehicles for homeland security surveillance and detection) to a very high Re (hypersonic vehicles for rapid global and space access). Across the Re range, unsteady, complex flow phenomena associated with transitional, turbulent, and separating boundary layers play an important role in aerodynamics and propulsion efficiency of these vehicles [1, 2]. Therefore, the ability to obtain quantitative, time-resolved shear stress measurements may elucidate complex physics and ultimately help engineers improve the performance of these vehicles [3]. Furthermore, since shear stress is a vector field, it may provide advantages over pressure sensing in active flow control applications involving separated flows [4]. Unfortunately, the time-accurate, continuous, direct measurement of fluctuating shear stress has not yet been fully realized [3]. MEMS–based devices with high-bandwidth and fine spatial resolution offer the potential to capture physics of the relevant length scales in at least moderate Re flows.

Several research groups have reported MEMS shear stress sensors of both direct and indirect types. Indirect sensors infer the wall shear-stress via the measurement of a different flow property and include thermal devices [5-7], laser-based sensors [8], micro-pillars [9, 10] and micro-fences [11]. Direct sensors measure the integrated shear force on a floating-element structure [12-20]. Three transduction schemes have been used in micromachined devices to determine the movement of the floating element: capacitive [12, 15, 16, 19], piezoresistive [13, 20] and optical [14, 17, 18]. While these existing sensors represent positive steps towards an instrumentation-grade measurement device, they are all unfortunately limited by sensitivity drift, limited bandwidth and/or an unacceptably high minimum detectable signal (MDS). We have attempted to address the limitations of existing floating element sensors via the development of a side-implanted piezoresistive sensing scheme.

The sensor structure integrates laterally-implanted diffused resistors into the sidewall of the sensor tethers for detecting the deflection of the floating element. Figure 1 shows an isometric view of the floating element, sidewall implanted p-type silicon piezoresistors, heavily doped end-cap region, and bond pads. In this transduction scheme,

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