Sensors and Actuators A 280 (2018) 359–367

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Development of a micromachined accelerometer for particle acceleration detection

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ARTICLE INFO

Article history:
Received 12 April 2018
Received in revised form 21 June 2018
Accepted 30 July 2018
Available online 9 August 2018

Keywords:
Accelerometer
Capacitive
Low-noise
Wide bandwidth
MEMS

ABSTRACT

We are reporting on the design, fabrication, and experimental results for a micromachiend accelerometer that is intended to be used in the detection of acoustic signals, where the main requirements include low noise, wide bandwidth, and high linearity. The device design requirements are discussed and analytically modelled. Microfabrication details to build prototypes are provided in detail. The final device structure employs membrane as the suspension mechanism and a proof-mass made from the entire thickness of a wafer that is suspended above a fixed electrode. The proposed manufacturing process allows for precise and independent control of the structural components of the device and the capacitive gap. Prototype devices were fabricated and characterized. Measurements on the device performance demonstrate a $0.6\,\mu g/\sqrt{Hz}$ noise floor with resonance frequency of 5.2 kHz, sensitivity of ~0.9 pF/g, and open-loop dynamic range of higher than 145 dB while operating at atmospheric pressure. The device meets the requirements for measuring sonar signals in the range of 50 Hz to 5 kHz under low environmental noise conditions.

1. Introduction

Numerous applications requirehigh-performance accelerometers including earthquake early warning systems, structural and machinery health monitoring, oil and gas exploration, threat detection, and search and rescue missions. A particularly interesting application field is detection of acoustic signals using accelerometers to not only estimate the magnitude but also the direction of an incoming acoustic signal. The combination of these information lets an array of such devices be used for localization of the acoustic source. As acoustic waves travel through compressible media such as air or water, they displace the molecules. The acceleration applied to the molecules is called *particle acceleration* and can be measured with an accelerometer whose dimensions are sufficiently smaller than the acoustic wavelength in the medium [1]. Micromachined accelerometers have been considered for this application since the 1990s [2–4]. Besides size, the other requirements for an accelerometer to be used as a particle acceleration sensor include low noise, wide bandwidth, and high dynamic range. On the other hand, parameters such as bias stability and drift are of lower importance as the bandwidth of interest typically starts from few tens of hertz, letting the user filter out the near-DC imperfections. For an accelerometer to be used as an underwater particle acceleration sensor for underwater threat detection, for instance, it needs to meet the strict requirements, including a noise level of less than $0.5\mu g/\sqrt{Hz}$ (corresponding to the ambient noise at sea state 1), bandwidth of ~5 kHz, and a high dynamic range, as the device need to be able to operate in active sonar systems [5].

Despite several decades of research, accelerometers based on microelectromechanical systems (MEMS) technologies often do not meet the combination of the noise floor, bandwidth, and dynamic range requirements for acoustic particle acceleration detection. Fig. 1 compares the noise and bandwidth of several high-performance micro-accelerometers reported in the literature. As seen, the highest performance sensors (in terms of resolution and bandwidth) employ optical transduction to detect the movements of the device proof-mass. The high resolution and speed of an optical interface allows for the detection of small proof-mass displacements, and hence, not only improving the noise performance, but also enabling their use in wideband accelerometer designs. Using optical transduction, Krause et al. reported an accelerometer where the acceleration is measured using a planar photonic-crystal nano-cavity that was monolithically integrated with a high Q-factor mass-spring system. The noise floor and bandwidth of the

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https://doi.org/10.1016/j.sna.2018.07.058
0924-4247/

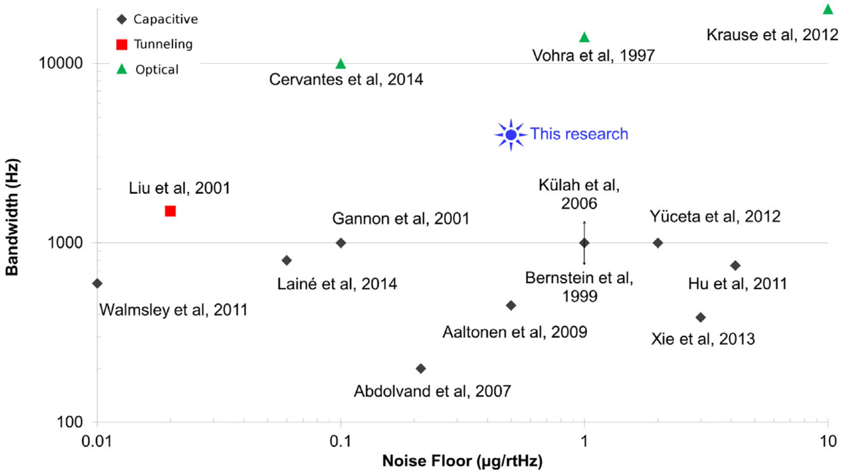

Fig. 1. Comparison of micro-accelerometers based on reported performance of bandwidth and noise floor [4,13,15,17–26].

accelerometer were reported as 10 $\mu g/\sqrt{Hz}$ and 20 kHz, respectively. However, the dynamic range of the accelerometer was limited to 40dB [6]. Vohra et al. reported a high-performance fiber optic accelerometer with less than 1 $\mu g/\sqrt{Hz}$ of noise at *1* kHz as well as a broad frequency response ranging from 100 Hz to 14 kHz [7]. The working principle of the reported accelerometer was based on the path length change of a fiber interferometer integrated with the proof-mass. A wide bandwidth along with a sub- $\mu g/\sqrt{Hz}$ noise floor was reported for another opto-mechanical accelerometer developed by Cervantes et al. [8]. This optical accelerometer was built from a combination of a mechanical fused-silica oscillator and fiber-optic micro-mirror cavities. The noise floor of this device was reported to be 100 $ng/\sqrt{Hz}$ for frequencies between 1.5 kHz and 10 kHz. Optical transducers, however, require special interface and packaging that can add to the complexity and cost of a system designed based on them. While the developments in the fields of photonic circuits and interfaces will enable wider-scale adaptation of optical devices in coming years, a device with electrical interfaces can be integrated more easily into existing systems.

A high-performance accelerometer is the device developed by Rockstad et al. [9] and further enhanced by Liu et al. [10,11]. They progressively developed accelerometers that employed electron tunnelling transduction aimed at underwater acoustics applications. The most recent version of such accelerometers operate at a low package pressure of 1.3Pa to achieve a noise level of 20$ng/\sqrt{Hz}$ [11]. The mechanical bandwidth of the system was increased from its resonance frequency of 100Hz to around 1kHz using a feedback controller. This device, however, required a complicated manufacturing process and a sophisticated controller for the highly nonlinear tunneling transduction.

The remaining accelerometers summarized in Fig. 1 are capacitive accelerometers. Considering mass-production challenges and system integration based on numerous sensors (e.g., >1000 sensors used simultaneously for towed arrays in sonar applications), presently capacitive devices are preferred due to their simple manufacturing, interfacing, and packaging requirements. Majority of these devices traded noise performance with bandwidth [9,12,13]. Gannon et al. developed a capacitive analog servo accelerometer [14]. The noise level of the accelerometer was 100$ng/\sqrt{Hz}$ with a bandwidth and dynamic range of 200Hz and 115dB, respectively. The sensor was a 3-terminal capacitive accelerometer which used a parallel-plate capacitor configuration. Some lower-performance versions of the reported accelerometer were later commercialized and sold by Colibrys [15]. Walmsley et al. developed a two-axis, in-plane capacitive MEMS accelerometer using the surface electrode technology [16–18]. The noise level of the accelerometer was reported as 10$ng/\sqrt{Hz}$ at a full bandwidth of 200Hz with a dynamic range of 120dB. Laine et al. developed a capacitive low-noise accelerometer with an 800Hz closed-loop bandwidth [19]. The accelerometer had a reported noise level of 10$ng/\sqrt{Hz}$ at 70Hz with a dynamic range of 130dB. The sensor, which used a transverse comb capacitance configuration, was commercialized as part of a land seismic acquisition system [20].

As summarized in Fig. 1, despite the ongoing interest and efforts in the field, meeting the bandwidth and dynamic range requirements simultaneously has remained an obstacle on the development of low-noise capacitive devices with bandwidths of more than 1 kHz. There has been no capacitive accelerometers that can simultaneously meet a noise floor of less than 1$\mu g/\sqrt{Hz}$ and bandwidth of more than 1 kHz, as is needed in applications such as sonar wave detection. This paper presents a combination of capacitive out-of-plane mechanical design and micro-fabrication process that lead to working devices with sub- $\mu g/\sqrt{Hz}$ noise levels, 5kHz resonance frequency, and high open-loop dynamic range for particle acceleration measurement for underwater acoustic wave detection. We first describe the device structure followed by analytic and numerical modeling of the device performance. Subsequently, the developed micro fabrication process to realize the designed accelerometer is presented. This is followed by experimental verification of the device performance. The paper ends by summarizing the contributions of the work.

2. Device design

The presented device was designed to meet the requirements for particle acceleration measurement for underwater acoustic waves. The main requirements are measurement bandwidth of 50 Hz to 5 kHz to detect signals produced or reflected from underwater objects, a noise level of better than 0.5 $\mu g/\sqrt{Hz}$ to measure signals above the ambient noise level of sea state 1, and high dynamic range (>130 dB) so that the device can remain operational if used in an active sonar system. A final design requirement imposed by the size limitation of the array for the particle acceleration sensors in this application, is that the chip needs to be less than 1 cm on its side, so that the packaged device would have a diameter of less than 2 cm (the cavity of the package is 12 mm × 12 mm).

2.1. Governing equations

For a capacitive device where the gap d_0 between two electrodes with areas A changes in response to proof-mass displacements, the sensitivity, defined as the rate of change of the output signal (i.e.,