Sound & Vibration 2025, 59(2), 3188.
https://doi.org/10.59400/sv3188

Editorial

Editorial: Recent trends in acoustic sensor applications

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CITATION

Gouda MM. Editorial: Recent trends in acoustic sensor applications. Sound & Vibration. 2025; 59(2): 3188. https://doi.org/10.59400/sv3188

ARTICLE INFO

Received: 9 May 2025
Accepted: 13 May 2025
Available online: 20 May 2025

Abstract: Acoustic sensor technology opens opportunities in various fields, particularly quartz crystal microbalance (QCM) and surface acoustic wave (SAW) technologies, which are known for high sensitivity, real-time detection, and non-invasive features. These sensors use mechanical waves to respond to external disturbances like mass changes or viscoelastic alterations, making them effective for monitoring chemical and biological processes, including biomolecules, volatile organic compounds, and pollutants. This adaptability enables applications. Therefore, in the Sound and Vibration journal, we invite the authors to submit related topics to attract interested scientists.

Keywords: acoustic sensors; QCM; SAW; piezoelectric materials; biomolecule sensation

1. Introduction

In recent years, advancements in acoustic sensor technology have been increased by the demand for more sensitive, stable, and versatile devices [1]. Traditional piezoelectric materials, such as quartz and lithium niobate, are increasingly being replaced or enhanced with novel materials like graphene oxide and reduced graphene oxide, which provide superior sensitivity and a broader range of applications [2,3]. This shift has significantly expanded the detection capabilities of acoustic sensors, allowing them to identify various analytes, including biomolecules, volatile organic compounds, and pollutants in both air and water. Consequently, these sensors have become indispensable tools in environmental monitoring and biomedical applications [4].

2. Recent developments in novel materials and their technical terms

Piezoresistive sensors effectively detect mechanical load deformation by modifying their electrical resistance. This process enables the conversion of sound pressure into an electrical output, facilitating the analysis of acoustic characteristics. The principle of the piezoresistive effect is observable in materials such as metals, semiconductors, graphene, and hydrogels. Notably, while resistivity in metals remains constant, resistance changes are primarily geometric, resulting in lower sensitivity than in semiconductors. Nonetheless, metals are readily fabricated on flexible polyimide substrates, making them suitable for strain sensors, particularly in acoustic applications. Ductile metals like gold, silver, copper, and aluminum excel in flexible electronics due to their advantageous mechanical properties. However, their reactivity presents challenges; contact with body tissues can release metal ions, necessitating encapsulation in biocompatible polymers. Furthermore, recent trends indicate a shift in acoustic sensor technology away from conventional piezoelectric materials, such as quartz and lithium niobate, toward innovative materials that enhance performance and expand applications. This evolution marks a significant advancement in the design and utilization of acoustic sensors across various fields.

Graphene-based materials are highly praised for their exceptional conductivity and advantageous surface-to-volume ratios [3,4]. These acoustic materials demonstrate remarkable flexibility and superior mechanical properties, enabling accurate detection of mechanical signals. Their favorable thermoacoustic and piezoresistive effects further enhance their performance in acoustic devices, facilitating sound detection and emission. Notably, Wang et al. [5] developed a device utilizing laser-induced graphene, which exhibited both piezoresistive and thermoacoustic properties for precise pressure detection. This system displayed exceptional sensitivity, responding to 12 relative current changes and achieving a rapid 50 ms response time at a 10 kPa pressure. In addition, Cui et al. [6] developed a quartz chip SAW sensor that achieved a response time of less than 1 sec and a detection range covering various gases and humidity levels, thus ensuring accurate sound responses for unique mechanical properties and chemical stability rendering free-standing microstructures, such as cantilevers and diaphragms, essential for acoustic sensors.

Among the novel acoustic materials are MXenes, a class of two-dimensional transition metal carbides and nitrides that emerge as promising materials for acoustic sensing applications [7]. Their integration with soft polymeric substrates enhances stretchability compared to traditional metal or semiconductor sensors. Furthermore, the development of biomimetic superhydrophobic surfaces significantly improves corrosion resistance. Notably, researchers have created a cotton-based superhydrophobic polypyrrole/MXene pressure sensor, which remains stable in wet conditions and sustains performance over 1000 cycles [8,9]. This advanced sensor effectively monitors physiological signals across various body parts, exhibiting a detection range of 0–80 kPa and high sensitivity in the 0–2 kPa range [10]. Collectively, these innovative materials underscore the potential to transform acoustic sensor technology, leading to more sensitive, selective, and versatile applications.

3. The emergence of nanotechnology in acoustic sensation

The integration of nanotechnology amplifies sensor sensitivity and enables miniaturization. For example, Zheng et al. [11] integrated Titanium dioxide (TiO_2) nanoparticles into SAW devices to modify the acoustic wave propagation, allowing for the detection of specific environmental pollutants through changes in frequency or amplitude. Collectively, these advancements provide valuable insights for guiding future research directions in sensor technology. Practically, Hung et al. [12] have used silver (Ag) silver nanoparticles–graphene–polypyrrole hybrid nanocomposite film for Ecoflex to demonstrate superior mechanical and electrical properties, facilitating applications in wearable thermotherapy patches and mechano-acoustic sensing of low ammonia concentrations. Furthermore, biocompatible metals such as Pt, Au, and Ti are effective contacts or sensors in wearable devices without requiring intricate encapsulation [13]. These sensors also feature two layers of gold nanowires for detecting larger signals, such as finger touches. Jean et al. [14] mentioned that polyvinylidene fluoride (PVDF), lead zirconate titanate (PZT), and zinc oxide (ZnO) nanofibers could achieve a low detection limit of 0.01% with a sensitivity up to 0.95 Pa^{-1}, thereby enabling the detection of vital signals, including the human carotid artery pulse and respiration sensations.

4. Acoustic sensors and dynamic biology

Comprehensively used for dynamic tracking acoustic sensors for biological processes, such as detecting disease biomarkers and observing cellular behavior. [15,16]. For instance, Alshraim et al. [17] examined the MXene-based QCM hydrophilicity across glucose concentrations. They concluded that the QCM nanocomposite system proved its suitability for real-time glucose monitoring within 3–10 mM concentrations and a detection limit as low as 1.70 mM in blood. In industrial settings, these sensors are crucial for detecting trace amounts of chemicals, pollutants, and gases in real-time, offering a noninvasive and continuous monitoring solution that is invaluable for air quality control and environmental protection [18]. However, one of the notable challenges in acoustic sensor technology is its susceptibility to environmental factors like humidity, temperature, and vibration, which can interfere with accuracy.

Recent advancements have developed methods to reduce external interference, boosting sensor reliability in real-world situations. For example, dual-delay line SAW sensors coated with bacterial cellulose (BC) effectively compensate for thermal and humidity variations. These BC-SAW sensors show excellent short-term repeatability and long-term stability, making them ideal for dynamic settings. Moreover, incorporating microcavities in the design enhances signal sensitivity by capturing energy near the surface, minimizing losses, and improving performance. Integrating microfluidic systems into acoustic sensors also allows precise control over the sample environment, reducing environmental influences. This has proven effective for real-time monitoring of cell adhesion and protein interactions and for identifying chemical pollutants in air and water [4,19].

5. Potential of acoustic sensor modulation in advanced fields

Beyond their analytical capabilities, acoustic sensors are emerging as significant tools in precision applications, particularly within personalized medicine. Their ability to monitor cellular activities and biochemical processes in real-time positions them at the forefront of innovative health solutions [20,21]. For instance, Mao et al. [22] assessed the photoacoustic dual-modal probe for visualizing liver injury and diagnosing sepsis that could identify the cancer biomarkers in human tissues. This high sensitivity allows for detecting biomarker levels at extremely low concentrations, down to 10 mg/L, which can be crucial for early disease detection and diagnosing conditions like bacterial infections and inflammatory diseases [23,24].

In addition to diagnostic applications, acoustic sensors are being explored for their ability to modulate cellular environments for therapeutic purposes. Love wave sensors, for example, have been employed to study the viscoelastic properties of cell membranes. This research provides valuable insights into how cells respond to various therapeutic agents. By leveraging these technologies, there is potential for developing non-invasive treatments that can effectively modulate cell behavior through targeted acoustic wave stimulation. Together, these advancements highlight the dual role of acoustic sensors in diagnostics and therapeutic modulation, paving the way for improved patient care in personalized medicine [25].

6. Artificial intelligence's importance in acoustic data interpretation

Artificial intelligence (AI) algorithms significantly enhance sensor data processing, improving detection accuracy and efficiency [26,27]. Specifically, they elevate the interpretation of acoustic data by utilizing advanced machine learning (ML) and deep learning (DL) techniques [28]. Indeed, distributed acoustic sensing (DAS) technology senses sound or vibration by measuring phase changes of light transmitted through a fiber optic. For this sensing technique, Yin et al. [29] introduced a novel denoising method based on data fusion for processing random and coherent noise in distributed fiber optic acoustic-sensing vertical seismic profile (VSP) data. In deeper explanation, the application of denoising convolutional neural networks (DnCNN) has significantly enhanced the clarity of the piezoelectric sensor (STZ) vibration signals, with studies by Shao et al. [30] showing an increase in the signal-to-noise ratio (SNR) from 13.4 dB to 42.8 dB. This improvement enables more accurate detection of acoustic events by preserving essential signal features while suppressing noise, thus enhancing the reliability of the DAS systems. As a result, these advancements support essential operational areas such as predictive maintenance, enabling precision identification and intelligent decision-making with minimal human intervention. Thus, AI significantly advances acoustic data interpretation through high-accuracy signal detection, efficient real-time processing, diverse applications, enhanced sensor performance, and predictive analytics, fostering innovation across multiple sectors [31].

7. Conclusions and future remarks

The innovations in acoustic sensor design, such as the incorporation of novel materials and integration with microfluidic and optical technologies, have significantly enhanced their performance and expanded their range of applications. Furthermore, the potential modulation of acoustic sensors in cellular environments offers exciting prospects for non-invasive treatments. As these technologies continue to evolve, their integration with other sensor types promises to unlock new capabilities, making acoustic sensors indispensable tools in research and large-scale applications.

When comparing acoustic sensors with other sensing technologies, it becomes clear that their integration with optical, electrochemical, and other biosensors can enhance their capabilities, making them more versatile and practical for complex applications. For example, combining SAW sensors with optical technologies, such as Raman spectroscopy and fluorescence-based imaging, offers improved sensitivity and selectivity for detecting specific molecules in complex biological samples. The combination of these technologies creates a powerful toolset for researchers and clinicians alike, enabling the development of highly sensitive, specific, and adaptable systems for various applications, from environmental monitoring to biomedical diagnostics and therapies. Moving forward, the focus should be on refining these technologies, addressing remaining challenges, and exploring their full potential in real-world applications.

Institutional review board statement: Not applicable.

Informed consent statement: Not applicable.

Funding: The author would like to thank the Academic Publishing Group for supporting the current manuscript publication. Also, thanks to the China-Egypt "Belt and Road" joint project between Zhejiang University and the National Research Centre (SQ2023YFE0103360) for supporting this work.

Conflict of interest: The author declares no conflict of interest.

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