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MODULATED ULTRASOUND MEMS LOUDSPEAKERS – A PARADIGM SHIFT

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Abstract

In recent years, loudspeakers that generate audible sound by demodulating an ultrasonic carrier have gained increasing attention. For MEMS applications in particular, this approach offers the advantage of achieving higher sound pressure levels at low frequencies, a regime in which conventional MEMS loudspeakers typically struggle to meet industry requirements. This advantage originates from a fundamental change in the loudspeaker's operating principle: Classical loudspeakers act as a volume source, whereas modulated ultrasound loudspeakers act as a volume flow source, enabling a +20 dB per decade increase in sound pressure for decreasing frequencies. This fundamentally different operation is achieved by introducing a shutter that demodulates the ultrasound carrier signal in order to create an audible signal. In this contribution, we review the current status of modulated ultrasound principles and outline their challenges in both technological and medical contexts. Besides fabrication, the topics of ultrasound tolerance in humans and animals, simulation methods, design optimization, and sound quality are tackled. Additionally, we compare modulated ultrasound principles with current MEMS loudspeaker designs and identify opportunities and application examples enabled by this new MEMS loudspeaker technology.

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Introduction

Over the past five years in particular, modulated ultrasound loudspeakers have attracted growing interest from both academic and industrial research, resulting in a steadily increasing number of publications on different pumping-based sound-generation principles [1], [2], [3]. This trend is further reflected by patents covering specific embodiments of such pumping mechanisms, filed by e.g. SonicEdge, xMEMS, Infineon, and Bosch. Broadly speaking, the operating principles found in the literature fall into two categories. Amplitude modulation schemes, such as Advanced Digital Sound Reconstruction (ADSR) [4], adapt the sound signal by varying stroke levels, whereas frequency modulation schemes [2] instead encode the audio signal in the frequency difference between a driving and a shutter membrane. A further complication when describing pumping speakers stems from the fact that they can be approached from two rather different perspectives [5]: Viewed as an ultrasound-pulse-based process, the sound generation is governed by overlapping discrete sound pulses, as is the case for ADSR [1]. From a signal-processing perspective, the same mechanism can equally be interpreted as a form of ultrasound modulation [2]. Both perspectives are addressed in the following section, where the respective principles are discussed in greater detail.

Operating principle

To ease the discussion of the underlying operating principle, a generic three-membrane embodiment, shown in Fig. 1, serves as a reference throughout this section. Two components are essential for any pumping speaker of this kind: a driving membrane, which generates the bulk of the volume flow, and a shutter, or demodulator, which steers this flow between two distinct channels. In the sketch shown in Fig. 1, the two upper channels form the main channel responsible for audio generation, while the two lower channels redirect flow into the speaker cavity below the speaker, a region that typically does not contribute to the sound generation process. It is important to note that the shutter movement has a decisive influence on the resulting sound generation. The sound radiated directly by the shutter is assumed negligible, an assumption that holds provided the shutter moves horizontally, as is the case for the configuration in Fig. 1. With this in mind, the individual sound generation principles can be distinguished as follows:

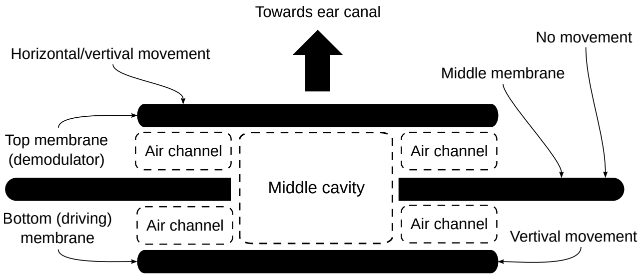

Figure 1: Sketch of a pump speaker using three membranes.

- Double sideband suppressed carrier (DSBSC) modulation:
  Amplitude modulation of the carrier (driving) membrane forms the basis of sound generation. Driving the shutter in phase with the carrier membrane produces a demodulation effect that results in a net volume flow. At its simplest, this net flow manifests as a sequence of individually generated sound pulses, each scaled by the instantaneous amplitude of the audio signal, such that their envelope reproduces the audio signal itself [1]. It is important to note that the name is only descriptive when the shutter/demodulator is moving horizontally. For vertical motion, the shutter itself contributes to sound generation at the carrier frequency [2]. Nevertheless, under idealized conditions, no carrier signal would be visible in the spectrum, hence the name DSBSC.
- Advanced Digital Sound Reconstruction (ADSR):
  Building on the principle of DSBSC, ADSR distributes the sound-generation task across several groups of unit cells, each of which operates according to the DSBSC principle. By introducing a defined phase shift between these unit cells, the superposition of their respective sound pulses yields a continuous audio signal with strongly reduced ultrasound content [1].
- Single sideband (SSB) modulation:
  In contrast to the two amplitude-based schemes above, SSB relies on frequency modulation: the carrier and shutter membranes are driven with a deliberate frequency offset corresponding to the audio signal rather than in phase [1]. Whereas DSBSC generates each sound pulse at maximum efficiency and merely rescales it according to the signal amplitude, SSB instead makes use of the demodulation process's dependence on the relative phase between the carrier and the shutter membrane [5]. As a consequence, the achieved demodulation efficiency fluctuates over time, producing pulses whose efficiency – understood here as the net volume displaced per pulse generated – varies accordingly.

Regardless of the actual driving principle used, all share decisive differences from classical loudspeaker operation. First of all, the sound generation is primarily influenced by the excitation in the ultrasound range, meaning that a low-frequency audio signal can be steered with high-frequency actuator excitation/movement. This is especially useful for MEMS applications due to the inherently high resonance frequencies of MEMS actuators, which can be used to increase the efficiency of the system. Additionally, the fundamental characteristic of the loudspeaker is changed, enabling a +20 dB increase in sound pressure level for decreasing frequencies regardless of the acoustic load condition. Nevertheless, driving the actuator in the ultrasound range inherently produces ultrasound as a by-product that must be adequately addressed.

1. Sound from ultrasound – where we are today

Due to the fact that the generation of audible sound using an actuator driven in the ultrasound range is a relatively new idea, the question arises, which gaps are yet to be filled. In the following, this question is subdivided into multiple areas to identify the current state as well as the gaps in the corresponding areas.

1.1. Operating principle

The first major unknown is the operating principle itself. Although the previously elaborated principles have already been studied in the literature [1], [3], the technology is not yet on the market and is still too new to ensure that all possible alterations of the principle are already established. As already shown by Mayrhofer [1] and Chen et al. [3], the actual embodiment changes efficiency, ultrasound content, and complexity. Besides the excitation signals altering the principle as described above, the movement direction of e.g. the shutter has a strong influence on the ultrasound content and complexity [3]. A horizontally moving shutter, for example, does not add an additional ultrasonic carrier in the spectrum of the radiated sound, but is more complex to realize in a MEMS application. Regarding the membrane mainly responsible for the sound generation, it can also be said that besides classical membrane or plate structures, also bi-stable operation should be taken into account [6]. Bi-stability could increase the potential output of the device at the cost of more non-linearity and potential ultrasound content in the radiated signal. Because of its effect on ultrasound content, the operating principle is inherently connected to the effects of ultrasound exposure on humans and animals. Overall, it can be said that regarding the operating principle, the literature is still relatively sparse due to the innovative nature of the operating principle.

1.2. Fabrication

The choice of operating principle is closely connected to fabrication, since the device's complexity strongly influences its manufacturability and reliability. Additionally, the choice of driving principle (electrostatic/piezoelectric) directly influences the potential embodiments and therefore again the operating principle itself. Up to now, the two main methods that have been used to drive MEMS loudspeakers are the electrostatic and the piezoelectric driving principle [7]. It is of course not guaranteed that this is also the best choice for modulated ultrasound speakers, but the proximity to classical MEMS loudspeakers as presented by Gazzola et al. [8] hints in this direction. Electrostatic devices are well established, as seen in the electrostatic microphone, and offer the advantage of lower capacitance. The cost of this driving principle, though, is the inherent non-linearity of a simple single back-plate actuator combined with the relatively small deflection at reasonable voltages compared to piezoelectric devices. The piezoelectric principle for actuators is also well established and is often the go-to variant for current MEMS loudspeakers in the literature [7], [9]. Here, the main disadvantage is the material itself – lead zirconate titanate (PZT) has a good coupling coefficient but contains lead, whereas alternative materials like aluminium nitride (AlN) or scandium aluminium nitride (ScAlN) avoid problematic compounds at the cost of lower coupling coefficients [10]. Additionally, the higher capacitance is a detrimental parameter when it comes to energy efficiency – especially when driving the speaker with an ultrasonic carrier.

Beyond the choice of driving principle, the device's new, complex structure introduces an additional layer of complexity in the manufacturing process (a three-layered structure with comparably large displacement amplitudes in a very compact device). Here, manufacturability, crosstalk, and reliability are topics that are not really covered in the literature and need further research.

1.3. Modeling and simulation

The topic of modeling and simulation is especially of interest for MEMS devices due to the relatively high prototyping costs of external manufacturing as well as the high requirements with respect to the machines used for manufacturing. Therefore, a digital twin enabling the prediction of the performance of an actuator potentially reduces innovation costs. Current literature mainly focuses on finite-element multiphysics simulations [4] and on network models [2]. Regardless of the simulation technique, a particular challenge arises from the change in operating principle from the classical analogue excitation to modulated ultrasound. Due to the fact that the modulation of the acoustic channel height is vital for the demodulation to work, this geometric change needs to be incorporated into the simulation framework. For multiphysics simulations this means that computations on moving domains are a fixed requirement to capture the dynamics of the actuator. Other important effects include the geometry-updated dependent electrostatic force as well as the squeeze-film effect and viscous effects in general [11]. Depending on the actual size of the actuator, molecular effects may also play a role which can be tackled with special boundary conditions. Such molecular effects appear when the Knudsen number is too high and continuum theory breaks down, giving rise to the significance of particle interactions. Due to the complex nature of the simulation framework, long simulation times are to be expected for full 3D simulations. Especially for changes in the operating principle, a full simulation has the benefit of including all necessary effects and uncovering potentially unknown interconnections at the cost of simulation speed. Although simulation frameworks such as `openCFS` can already simulate modulated ultrasound loudspeakers [4], today's short innovation cycles demand fast and accurate computations. To meet this demand, computational efficiency should be prioritized, which can be achieved through model order reduction techniques [12] and extensions to other modeling tools such as the boundary element method [13] and machine learning [14]. Based on fast and accurate 3D simulations, the next step should then be to deduce even faster and more efficient network models for design sweeps and optimization strategies, as already done for MEMS loudspeakers working with the classical operating principle [15].

1.4. Effects on humans and animals

Since there are no long-term studies on the effects of modulated ultrasound loudspeakers on humans and animals, it is vital to adhere to current guidelines and advance research in these areas to ensure their safe operation. Currently, ultrasound exposure is a topic that has not been tackled in-depth in the literature. There are publications that determine safe exposure levels for ultrasound hearing as well as guidelines [16], [17], but they rely on a comparably sparse dataset relative to the standard hearing range. It is of course possible to reduce the radiated ultrasound content of modulated ultrasound loudspeakers such that the exposure falls well below current thresholds; nevertheless, the potential scale of application gives rise to more detailed investigations to ensure safe operation. Hence, investigations with respect to the transmission and effect of ultrasound on humans via e.g. temporal bone experiments [18] is the first step to ensure safe listening experiences and accurate exposure limits. Additionally, the potential exposure of animals has to be considered. Imperfect sealings or even potential free-field applications expose humans and animals to ultrasonic emissions. However, cats, dogs, rats, and other pets have a different hearing range than humans, leading to a potentially different impact of ultrasound on them. To investigate the effects of acoustic or electrical stimulation on the entire organism and, in particular, on the auditory system, established animal models such as the rat are used [19], [20]. In contrast to humans, rats can hear ultrasound up to 80 kHz [21], making ultrasound processing a physiological component of their auditory system. Taken together, medical research in this field is very important for guiding and ensuring safety throughout the development of this new technology.

Besides the direct effects on humans and animals, it is also important to have access to accurate measurement equipment. Current couplers used to determine the frequency response of loudspeakers as well as sound immission measurement methods often only cover the human hearing range [22], [23]. For modulated ultrasound speakers, this is not enough due to the high carrier frequency as well as potentially higher harmonics. Here, new measurement techniques are required to accurately capture the complete picture of the actuators.

1.5. Application examples of modulated ultrasound loudspeakers

Besides the rather obvious application area of in-ear loudspeakers, hearing aids and other applications requiring compact form factors are prime examples for the applicability of modulated ultrasound loudspeakers. For hearing aids in particular, the occlusion effect as well as clicking sounds from moving parts can lead to discomfort of applicants [24], [25]. For modulated ultrasound loudspeakers, fast response times and very high SPL at low frequencies, combined with the absence of moving parts, could give them an edge over conventional loudspeakers in terms of comfort and sound quality. Nevertheless, there is a multitude of other potential applications – ranging from occluded to free-field applications that are yet to be explored. Providing an outlook on potential applications is a rather difficult task, since the technology is so young, meaning that in-depth analysis is yet to be done. Nevertheless, the potential application examples can already be taken from the ones of classical loudspeakers – whether all of them are sensible is another question. Additionally, potential new application fields could be uncovered due to the change in form factor of the speaker.

Summary, Conclusion and Outlook

In this contribution, we have given an overview of the operating principles underlying modulated ultrasound loudspeakers, distinguishing between the amplitude-based DSBSC and ADSR schemes and the frequency-based SSB modulation. Regardless of the specific principle, all approaches share the characteristic of using ultrasonic excitation to steer a comparatively low-frequency audio signal, which inherently produces ultrasound as a by-product that must be addressed. Nevertheless, the fundamental advantage of having a +20 dB increase in sound pressure level for decreasing frequencies strongly supports the viability of MEMS loudspeakers.

Based on this overview, several gaps have been identified. The operating principle itself, fabrication choices between electrostatic and piezoelectric actuation, and the modeling and simulation of these devices all still require further research, particularly regarding computational efficiency. Furthermore, the effects on humans and animals remain insufficiently understood, and current measurement equipment does not adequately cover the relevant ultrasonic frequency range. Overall, it can be said that modulated ultrasound loudspeakers constitute a promising yet still emerging technology, and closing the identified gaps will be essential to fully realize their application potential.

References

[1] D. Mayrhofer, “A MEMS loudspeaker based on Advanced Digital Sound Reconstruction,” Ph.D. dissertation, TU Graz, Feb. 2024.

[2] S. Chen and M. Margalit, “Modulated Ultrasound Speakers - A Common Framework for Analyzing Air Pump Speakers,” *Sensors and Actuators A Physical*, vol. 381, 2024.

[3] S. Chen and M. Margalit, “Comparative analysis of active modulated ultrasound speaker architectures,” *Physica Scripta*, vol. 101, no. 4, p. 045 906, Jan. 2026.

[4] D. Mayrhofer, K. Roppert, D. Tumpold, and M. Kaltenbacher, “A Moving Mesh Method for Fluid-Solid-Acoustic Interactions in MEMS Devices,” *Journal of Theoretical and Computational Acoustics*, vol. 32, no. 04, p. 2 450 016, 2024.

[5] D. Mayrhofer, T. Wilczacki, and M. Kaltenbacher, “Overview and simulation of modulated ultrasound MEMS loudspeakers,” in *Proceedings of the 52nd German Annual Conference on Acoustics (DAGA)*, Dresden, Germany, 2026, pp. 911–914.

[6] M. Schneider, M. Dorfmeister, P. Moll, M. Kaltenbacher, and U. Schmid, “Bi-Stable Aluminum Nitride-Based Piezoelectric Micromachined Ultrasonic Transducer (PMUT),” *Journal of Microelectromechanical Systems*, vol. 29, no. 5, pp. 948–953, 2020.

[7] M. Garud and R. Pratap, “MEMS audio speakers,” *Journal of Micromechanics and Microengineering*, vol. 34, no. 1, p. 013 001, Nov. 2023.

[8] C. Gazzola, V. Zega, A. Corigliano, P. Lotton, and M. Melon, “A reduced-order-model-based equivalent circuit for piezoelectric micro-electro-mechanical-system loudspeakers modelling,” *The Journal of the Acoustical Society of America*, vol. 155, no. 2, pp. 1503–1514, 2024.

[9] H. Wang, Y. Ma, Q. Zheng, K. Cao, Y. Lu, and H. Xie, “Review of Recent Development of MEMS Speakers,” *Micromachines*, vol. 12, no. 10, 2021, ISSN: 2072-666X.

[10] S. Pandit, M. Schneider, S. Schwarz, and U. Schmid, “Enhancement of Piezoelectric Response in Yttrium Aluminum Nitride (YxAl1-xN) Thin Films,” *Advanced Engineering Materials*, vol. 25, Oct. 2023.

[11] A. Melnikov et al., “Balanced MEMS loudspeaker: Coulomb forces vs. viscosity of air and squeeze film damping,” in *Proceedings of the 47^{th} German Annual Conference on Acoustics (DAGA)*, Vienna, Austria, 2021, pp. 749–752.

[12] A. van de Walle, F. Naets, E. Deckers, and W. Desmet, “Stability-preserving model order reduction for time-domain simulation of vibro-acoustic FE models,” *International Journal for Numerical Methods in Engineering*, vol. 109, no. 6, pp. 889–912, 2017.

[13] D. Panagiotopoulos, E. Deckers, and W. Desmet, “Krylov subspaces recycling based model order reduction for acoustic BEM systems and an error estimator,” *Computer Methods in Applied Mechanics and Engineering*, vol. 359, p. 112 755, 2020, ISSN: 0045-7825.

[14] S. Schoder, “Physics-Informed Neural Networks for Modal Wave Field Predictions in 3D Room Acoustics,” *Applied Sciences*, vol. 15, no. 2, p. 939, 2025.

[15] C. Gazzola et al., “High Performance Mechanically-Open and Acoustically-Closed MEMS Loudspeakers for In-Ear Applications,” *Journal of Microelectromechanical Systems*, vol. 35, no. 2, pp. 250–260, 2026.

[16] European Parliament and Council, *Directive 2003/10/EC of 6 February 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise)*, Official Journal of the European Union, L 42, pp. 38–44, 2003. [Online]. Available: `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32003L0010`.

[17] World Health Organization (WHO), *Make Listening Safe*, Geneva, 2021. [Online]. Available: `https://cdn.who.int/media/docs/default-source/documents/health-topics/deafness-and-hearing-loss/mls-brochure-english-2021.pdf`.

[18] R. Rupp et al., “Cartilaginous bending spring tympanoplasty: a temporal bone study and first clinical results,” *European Archives of Oto-Rhino-Laryngology*, vol. 279, no. 11, pp. 5145–5151, 2022.

[19] N. Rosskothen-Kuhl and R.-B. Illing, “The impact of hearing experience on signal integration in the auditory brainstem: a c-Fos study of the rat,” *Brain Research*, vol. 1435, pp. 40–55, 2012.

[20] N. Rosskothen-Kuhl, A. N. Buck, K. Li, and J. W. Schnupp, “Microsecond interaural time difference discrimination restored by cochlear implants after neonatal deafness,” *eLife*, vol. 10, e59300, Jan. 2021.

[21] J. B. Kelly and B. Masterton, “Auditory sensitivity of the albino rat,” en, *J. Comp. Physiol. Psychol.*, vol. 91, no. 4, pp. 930–936, Aug. 1977.

[22] International Electrotechnical Commission (IEC), *Electroacoustics – Simulators of human head and ear – Part 4: Occluded-ear simulator for the measurement of earphones coupled to the ear by means of ear inserts (IEC 60318-4:2010)*, Geneva, Switzerland, 2010.

[23] International Organization for Standardization (ISO), *Acoustics – Determination of sound immission from sound sources placed close to the ear – Part 1: Technique using a miniature microphone inserted into the ear canal (MIRE technique), ISO 11904-1:2002; and Part 2: Manikin technique, ISO 11904-2:2021*, Geneva, Switzerland, 2002.

[24] C. Adams, U. Baumann, T. Stöver, and T. Weißgerber, “Klickgeräusche durch bewegliche Magnete bei Cochlea Implantaten: Fallbeschreibung und akustische Messungen,” *GMS Zeitschrift für Audiologie – Audiological Acoustics*, vol. 3, Doc01, 2021.

[25] F. Denk, T. Hieke, M. Roberz, and H. Husstedt, “Occlusion and coupling effects with different earmold designs – all a matter of opening the ear canal?” *International Journal of Audiology*, vol. 62, no. 3, pp. 227–237, 2023.