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On the theoretical maximum achievable signal-to-noise ratio (SNR) of piezoelectric microphones

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Abstract

A theoretical maximum achievable signal to noise ratio (SNR) for piezoelectric microphones is identified as a function of only microphone volume irrespective of architecture and construction details. For a given piezoelectric material, microphone SNR can be reduced to an expression containing only a dimensionless coupling coefficient and microphone volume. For a given material, the coupling coefficient has a theoretical upper bound defined by the most favorable deformation geometry. The ability to identify a theoretical maximum SNR as a function of only microphone size is surprising considering the numerous design variables and infinite design freedom afforded in the microphone design stage.

Keywords

Piezoelectric; microphone; SNR

1. Introduction

Piezoelectric MEMS microphones have been studied and developed for several decades [1–4]. Historically, potential advantages cited for piezoelectric MEMS microphones include no backplate, no required bias voltage, and a relatively large capacitance compared to capacitively transduced MEMS microphones. More recently, piezoelectric sensing has proven useful for prototyping microphones with unconventional geometries, such as microphones mimicking the hearing organs of insects [5–7] and human cochleas [8], and microphones employing dense cantilever arrays for “pre-filtering” captured sound [9].

There has also been recent interest in exploring SNR limits of piezoelectric MEMS microphones. Littrell et al. [10] illustrates how the relatively large capacitance of piezoelectric MEMS microphones, when compared to capacitively sensed microphones, results in less signal attenuation and smaller A-weighted noise contribution from the finite input capacitance and bias resistance of a JFET amplifier, respectively. More interestingly,

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[10] explores the SNR optimization of a piezoelectric microphone by maximizing output signal energy, and the perspective reveals that matching back-cavity compliance and transducer compliance maximizes captured energy. The energy maximization perspective in [10] also leads to insights regarding optimized electrode placements. The maximum achievable SNR is identified for several simple geometries, working under the assumption of a dielectric-loss limited noise floor.

In this work, this line of thinking is abstracted a level higher, and a maximum achievable SNR is identified for piezoelectric MEMS microphones as a function of only microphone volume, independent of construction or electrode placement details. The result is enabled by high-level analysis considerations. Inspired by the energy maximization perspective of Littrell, it is observed that the volume of a microphone alone dictates the amount of mechanical energy that can be stored, and the electromechanical coupling coefficient of the transducer in-turn dictates the electrical energy available for capture. Coupling coefficients have upper bounds defined by the most favorable deformation geometry for a given material, thereby enabling quantification of an upper limit achievable for any sensor, irrespective of internal design details.

The analysis and observations are facilitated with a general network model of the microphone system. Aside from enforcing linearity, this does not limit or restrict generality in any way. e.g. The parameters comprising the network model may be obtained with the most advanced numerical simulations or through direct measurement in the case of existing structures. The network is simply a convenient visualization of a coupled equation set relating salient parameters of the microphone.

2. Theory

Fig. 1 presents a schematic of a generic piezoelectric microphone with important attributes labeled. A deformable structure (e.g. cantilever or diaphragm) resides above a microphone back-cavity with volume Ψ and deforms under sound pressure P . The deformable structure at least partially comprises a region of piezoelectric material that generates an electrical signal (voltage = V , and/or charge = Q) when flexed.

This physical model has a corresponding network model presented in Fig. 2. The electrical port has an electrical capacitance whose value, as measured or computed under the condition of restricted motion of the deformable structure, shall be denoted C_{eb} , with the subscript “ b ” denoting “blocked.” The flow variable on the right-hand-side (RHS) of the network is acoustic volume velocity. C_{ad} is the acoustical compliance of the deformable structure, defined as the volumetric displacement imparted to the back-volume per 1 Pa of applied sound pressure (units of m^3/Pa). Similarly, C_{ab} is the acoustical compliance of the air comprising the back volume, and its numerical value depends only on the volume of the back-cavity, Ψ . Reading the network from right to left, the transformer ratio, Φ , is defined as the short-circuit charge generated across the piezoelectric electrodes per volumetric displacement of the deformable structure (units of C/m^3). For the following analysis, the transducer sub-system is defined as shown in Fig. 2, and the perspective is taken such that

C_{ab} is part of the load. Using this perspective, the load is comprised of pressure P with a source impedance element C_{ab} .

A coupling coefficient for transducers is commonly defined as the ratio of stored electrical energy to stored total energy under the action of a mechanical input, $k_T^2 = E_{\text{electrical}} / E_{\text{total}}$. For subsequent analysis there is utility in defining a coupling coefficient as the ratio of stored mechanical energy to stored electrical energy under the action of an electrical input, $k^2 = E_{\text{mechanical}} / E_{\text{electrical}}$. Inspection of the network in Fig. 2 leads to the following expression for k^2 :

$$k^2 = \Phi^2 \frac{C_{ad}}{C_{eb}}$$

k^2 is a convenient grouping of terms for subsequent analysis, and its relationship to the more commonly defined k_T^2 is $k^2 = k_T^2 / (1 - k_T^2)$.

It is well known that a fundamental noise source in piezoelectric sensors is thermal-electrical noise generated by dielectric leakage in the piezoelectric film [11]. This leakage may be represented with a resistance R in series with C_{eb} with value $R = \tan \delta / (\omega \times C_{eb})$, where $\tan \delta$ is the loss tangent of the material. The resistance generates a voltage noise

$v_n = \sqrt{4k_b T R} [V / \sqrt{\text{Hz}}]$ in series with C_{eb} . Alternatively, and equivalently through source transformation, v_n may be represented as a charge source $q_n = C_{eb} \times v_n [C / \sqrt{\text{Hz}}]$ in parallel with C_{eb} as shown in Fig. 2. For a dielectric-loss noise limited sensor, it is clear that the ratio of signal power to noise power SNR^2 in a 1 Hz noise bin is given by

$$\text{SNR}^2 = \frac{Q_{sc}^2}{q_n^2} = \frac{Q_{sc}^2}{C_{eb}^2} \times \frac{\omega}{4k_b T \tan \delta} \quad (1)$$

Following directly from Fig. 2,

$$Q_{sc} = \frac{P\Phi}{\frac{1}{C_{ad}} + \frac{1}{C_{ab}}}$$

and inserting into Eq. (1) yields

$$\text{SNR}^2 = \frac{P^2 \Phi^2}{\left(\frac{1}{C_{ad}} + \frac{1}{C_{ab}}\right)^2} \times \frac{1}{C_{eb}^2} \times \left(\frac{\omega}{4k_b T \tan \delta}\right)$$

Algebraic manipulation of this expression leads to

$$\text{SNR}^2 = k^2 \times C_{ab} \times \frac{r}{(1+r)^2} \times \left(\frac{P^2 \omega}{4k_b T \tan \delta} \right) \quad \left(r \stackrel{\text{def}}{=} \frac{C_{ad}}{C_{ab}} \right) \quad (2)$$

The last grouping in Eq. (2) contains only physical constants and a material property, and is not interesting from a design perspective. The lead three terms are most interesting. C_{ab} depends only on the size of the back-volume, so for a chosen microphone size, this parameter is set. r is a dimensionless ratio. As $r/(1+r)^2$ is maximized for $r=1$, Eq. (2) makes clear that SNR is maximized when $C_{ad} = C_{ab}$ (i.e. when the compliance of the deformable structure matches the compliance of the back-volume). In such case, $r/(1+r)^2$ is equal to 1/4. The only remaining parameter, k^2 , is a dimensionless ratio that, for given material properties, depends only on dimensionless geometrical design ratios of the deformable structure, and not on any absolute size or length scale. Eq. (2) is insightful because k^2 can be maximized independently of r , revealing that, for a chosen back-volume size and for a dielectric-loss noise limited sensor, k^2 is the only design parameter determining microphone SNR.

Under the circumstance $r=1$, Eq. (2) leads to:

$$\text{SNR}_{\text{matched}}^2 = \frac{1}{4} \times k^2 \times C_{ab} \times \frac{P^2 \omega}{4k_b T \tan \delta} \quad (3)$$

An analysis using open-circuit signal voltage instead of short-circuit signal charge results in precisely the same expressions for SNR^2 and $\text{SNR}_{\text{matched}}^2$. Eq. (2) and Eq. (3) make clear that SNR is proportional to electrical signal energy. In the case of short-circuit charge read out, the optimal condition $C_{ad} = C_{ab}$ may be interpreted as a mechanical impedance matching condition for maximum mechanical energy captured by the transducer from sound pressure P . In this circumstance, the $\frac{1}{4} \times C_{ab} \times P^2$ grouping of terms in Eq. (3) is precisely the total mechanical energy delivered by sound pressure P . k^2 and k_T^2 represent the transducer's ability to convert captured mechanical energy to electrical energy.

3. Expressions for A-weighted Noise

A minimum detectable pressure (MDP) is commonly defined as the sound pressure that results in an SNR of unity. MDP is synonymous with input-referred noise. Using Eq. (3), it is clear that

$$\text{MDP}_{\text{matched}}^2 = \frac{16k_b T \tan \delta}{2\pi f} \times \frac{1}{k^2 C_{ab}} [\text{Pa}^2/\text{Hz}] \quad (4)$$

The A-weighted noise of the microphone is provided as

$$\text{Noise} = 10 \log_{10} \left(\int_{f_1}^{f_2} A^2(f) \times (\text{MDP})^2 df \right) - 10 \log_{10}(P_{ref}^2) [\text{dBA}] \quad (5)$$

where $A(f)$ is the A weight filter function [12]. Assuming isentropic compressions of the back-volume,

$$C_{ab} = \frac{\overline{V}}{\rho c^2}$$

[13] and substituting Eq. (4) into Eq. (5),

$$\begin{aligned} \text{Noise}_{\text{matched}} = & 10 \log_{10} \left(\frac{8}{\pi} k_b T \rho c^2 \right) + 10 \log_{10} \left(\frac{\tan \delta}{k^2 \overline{V}} \right) + \dots \\ & \dots 10 \log_{10} \left(\int_{f_1}^{f_2} A^2(f) \times \frac{1}{f} df \right) - 10 \log_{10}(P_{ref}^2) [\text{dBA}] \end{aligned}$$

so

$$\text{Noise}_{\text{matched}} = 10 \log_{10} \left(\frac{\tan \delta}{k^2 \overline{V}} \right) - 48.73 \text{ dB} \quad (5a)$$

SNR is commonly defined using a 1 Pa (or 94 dB SPL) signal reference, and the accompanying expression for SNR is

$$\text{SNR}_{\text{matched}} = 94 \text{ dB} - \text{Noise}_{\text{matched}} = 142.73 \text{ dB} - 10 \log_{10} \left(\frac{\tan \delta}{k^2 \overline{V}} \right) \quad (5b)$$

Eq. (5a) provides the A-weighted dielectric-loss induced noise floor of a piezoelectric microphone under the matched compliance condition as a function of only k^2 , microphone back-volume, and $\tan \delta$. As dielectric loss noise is a fundamental noise source, Eq. (5b) is an expression for the theoretical maximum SNR achievable of a piezoelectric microphone in terms of these three parameters.

4. Maximum Achievable SNR

Taking the analysis a step further, a maximum achievable SNR may be identified as a function of only microphone volume and piezoelectric material type. This is possible because, for a given a material, k^2 depends only on deformation geometry, and optimum configurations exist. e.g. For AlN, the highest possible k^2 is achieved when $T_1 = T_2 = 0$ and the material is strained along the 3 axis. This is the deformation geometry of the so-called 3-3 bar configuration. In this case, using properties of AlN from [14], $k^2 = 11.0\%$, a

maximum for AlN. A microphone employing AlN and with a back-cavity volume of 3.0 mm^3 has a theoretical maximum achievable SNR equal to 74.92 dB, following Eq. (5b) and assuming $\tan \delta = 0.002$ for AlN.

Contemplating a bar-like deformation geometry for the deformable structure in Fig. 1 would seemingly contradict the compliance matching requirement $C_{ad} = C_{ab}$ underlying Eq. (5), as bar geometries are stiff and do not necessarily provide the design flexibility required to achieve the matching requirement. It is possible, however, to envision designs that achieve the k^2 of a bar while also achieving the compliance matching condition -through levers. A simple conceptual example is provided in Fig. 3. If the plate is strictly rigid and does not store mechanical energy, k^2 of the entire system is equal to k^2 of the piezoelectric bar.

Common elemental deformation geometries are summarized in Fig. 4, and their respective k^2 values for two materials, AlN and PZT5H, are presented in Table II. Generally speaking, the k^2 of a deformable structure comprising an element is equal to the k^2 of the element only if:

- (Ci) non-piezoelectric regions of the deformable structure do not store mechanical energy (i.e. are infinitely stiff), and
- (Cii) equal stress resides in all regions of the piezoelectric element(s).

The 3-1 plate deformation geometry configured for bending is most commonly used for MEMS microphones -as this is the most easily implemented [2, 9, 15]. k^2 of the AlN 3-1 plate is 3.67%. k^2 of actual microphone structures utilizing the 3-1 plate in bending are typically less than this, as condition Cii above is not met. For example, for the common bimorph bending plate under uniform pressure loading, a non-homogenous stress in the piezoelectric material is inherent through both the thickness of the plate and along the length of the plate. The maximum k^2 achievable by a microphone employing an AlN 3-1 bending plate is 3.67%. Practical designs can only approach this number. For a back-volume of 3 mm^3 (typical of modern MEMS microphones), such a microphone has a theoretical maximum achievable SNR equal to 70.14 dB following Eq. (5b). Littrell identifies many designs employing AlN 3-1 plates in the bending mode [10]. All are subject to the constraint of Eq. (5b). In particular, [10] identifies clever placement of electrodes and the use of four electrodes in the bending configuration. These innovations enable the designs to approach $k^2 = 3.67\%$, but they cannot exceed this limit.

Fig. 5 and Eq. (5b) make clear that maximum attainable SNR increases 3 dB with each doubling in microphone size. Eq. (5b) also makes clear that the relevant material property influencing SNR is the dimensionless ratio $k^2/\tan \delta$. Table II summarizes this ratio as a function of deformation geometry for both AlN and PZT5H. The properties of microfabricated PZT vary widely and are not necessarily equal to those of PZT5H. Fig. 5 presents maximum theoretically achievable SNR vs. size for AlN 3-3 bar transduction and 3-1 bending plate transduction, following Eq. (5b) and values from Table II. The curves are a design frontier governed by material limitations. Practical designs lie below these curves and can only approach the frontier. Innovations in material processing technology and/or materials synthesis targeting increases in k^2 or reductions in $\tan \delta$ increase attainable SNR. As an example, in bending 3-1 plate configurations, ScAlN has recently demonstrated the

ability to achieve $2\times$ the charge output of AlN with minimal increase in dielectric constant [16], suggesting $4\times$ improvement in k^2 is possible over that of AlN.

5. Other Sources of Noise and Misc. Considerations

The focus of this article is to identify a maximum SNR limit for piezoelectric microphones - not to explore all sources of noise in MEMS microphones. Unlike many other sources of noise, dielectric-loss-induced noise cannot be avoided or reduced even through practice of design compromise and is therefore a fundamental detection limit. A few other sources of noise are briefly considered to explore to what extent achieving the dielectric-loss noise limit is possible.

With respect to electronics noise, a situation is considered in which an AlN transducer with 2.5 pF capacitance is input into a first stage FET with a 1.0 pF gate capacitance, $10 \text{ nV}/\sqrt{\text{Hz}}$ voltage noise, and 100 G Ω bias impedance. The dielectric noise is $32 \text{ nV}/\sqrt{\text{Hz}}$ at 1 kHz. A simple exercise in noise analysis including thermal noise from the bias impedance reveals that in such a scenario electronic noise is less than dielectric-loss induced noise from 1 Hz to 21 kHz.

Vent-induced thermal mechanical noise is also significant in miniature microphones, and is fundamental to any microphone configured with a vent to impart a lower limiting frequency, f_0 . A complete description of all packaging-induced noise sources is presented in several references, including [17–19]. The A-weighted vent noise contribution is completely determined by C_{ad} , C_{ab} , and f_0 . For an optimized compliance matched condition in which $C_{ad} = C_{ab}$, A-weighted vent noise is completely determined by back-cavity volume and f_0 . Fig. 6 plots A-weighted vent noise as a function of these two parameters.

Fig. 2 and the presented analysis deliberately exclude mass of the deformable structure and the acoustical mass of a microphone sound inlet - a feature common to practical MEMS microphone packages. Both are in series with the compliance of the deformable structure and determine the first resonance of a packaged microphone structure. The analysis has also deliberately excluded loss in the acoustical domain (e.g. due to inlet port resistance), which gives rise to thermal mechanical noise. If the first resonance of a packaged system is less than 20 kHz, A-weighted thermal-mechanical and vent noise contributions are increased due to their amplification in the vicinity of the resonance. These effects are seen in references [18, 19], for example. Ultra-miniature microphones may also be subject to back-volume noise, owing to non-isentropic compression of air comprising the back-volume [20].

As a final note, it is important to note that two A-weight functions are commonly used in the MEMS microphone industry: a true A-weight filter function as described in several references including [12], and an A-weight filter function including a brick wall cut-off at 20 kHz. The former option is used in this manuscript.

6. Conclusion

A maximum achievable SNR limit for piezoelectric MEMS microphones has been identified and quantified as a function of only piezoelectric material type and microphone volume. The insight is made possible by analyzing the system using a high level of abstraction. From a design perspective, an insightful expression from this analysis is Eq. (5a), expressing dielectric-loss-induced A-weighted noise in terms of only microphone back-volume, $\tan \delta$, and k^2 . For a chosen microphone volume and piezoelectric material, k^2 is the only remaining design parameter. The theoretical SNR maximums identified are design frontiers that practical microphone designs can approach but not exceed. Modern MEMS microphones have back-cavity volumes between 1 mm^3 and 3 mm^3 . For AlN, the maximum theoretical limit requires utilization of a 3-3 bar deformation geometry and is 70.15 dB for a 1 mm^3 microphone, and 74.92 dB for a 3 mm^3 microphone. The corresponding limits for the 3-1 plate deformation geometry are 65.4 dB and 70.1 dB, respectively. Example computations presented in this article have used AlN and PZT as these are two common materials employed by MEMS microphones. Eq. (5b) is applicable to a microphone employing any material, and the expression makes clear that attainable SNR increases with the ratio $k^2/\tan\delta$. Innovations in material synthesis that target increases in coupling coefficient and/or decreases in dielectric loss tangent can therefore increase attainable SNR as governed by Eq. (5b).

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Neal A. Hall received the B.S. degree in mechanical engineering from The University of Texas at Austin in 1999, and the M.S. and Ph.D. degrees in mechanical engineering from the Georgia Institute of Technology, Atlanta, in 2002 and 2004, respectively. From 2004 to 2006, he was an Intelligence Community Postdoctoral Fellow at Sandia National Laboratories, Albuquerque, NM. He joined the Electrical and Computer Engineering Department, The University of Texas at Austin, as an Assistant Professor in January 2009, where he performs research in the areas of silicon micromachined acoustic transducers, optics and photonics. Neal is a 2012 recipient of a DARPA Young Faculty Award (YFA) and a 2014 recipient of an ONR Young Investigator Award (YIA). He is also Founder and Chief Technology Officer of Silicon Audio, Inc.

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Fig. 1.
A generic piezoelectric microphone structure

Fig. 2.
A network model of a generic piezoelectric microphone structure

Fig. 3.
A conceptual representation of a transducer employing a 3-3 bar elemental deformation geometry.

Fig. 4. Schematic summarizing stress and strain for three common elemental deformation geometries.

Fig. 5.
Theoretical maximum SNR vs. volume for AlN 3-3 bar and 3-1 plate geometry microphones

Fig. 6.
A-weighted vent-induced noise as a function of back volume and f_0

Table I

Description of symbols used in the article

Symbol	Description	Symbol	Description
P	Sound pressure	q_n	Noise referred charge
V	Voltage at piezoelectric port	Q_{sc}	Short circuit charge
Q	Charge at piezoelectric port	$\tan \delta$	Dielectric loss tangent of piezoelectric material
Ψ	Back cavity volume	k_b	Boltzmann constant
$\delta \Psi$	Volumetric displacement	T	Temperature
C_{eb}	Blocked capacitance	ω	Angular frequency
C_{ad}	Acoustical compliance of deformable structure	ρ	Density of air
C_{ab}	Acoustical compliance of back cavity volume	c	Speed of sound of air
Φ	Transformer ratio		

Table II

The dimensionless ratios k^2 and $k^2/\tan \delta$ for common elemental deformation geometries of AlN and PZT5H. $\tan \delta = 0.002$ for AlN and 0.04 for PZT5H. Material properties for AlN are taken from [14]. Note that $k^2 = k_T^2 / (1 - k_T^2)$.

k^2	3-3 bar	3-3 plate	3-1 plate
AlN	0.110	0.068	0.037
PZT5H	1.310	0.363	0.484
$k^2 / \tan \delta$	3-3 bar	3-3 plate	3-1 plate
AlN	55.15	33.80	18.35
PZT5H	32.76	9.08	12.09