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A microacoustic analysis including viscosity and thermal conductivity to model the effect of the protective cap on the acoustic response of a MEMS microphone

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Abstract

An analysis is presented of the effect of the protective cover on the acoustic response of a miniature silicon microphone. The microphone diaphragm is contained within a small rectangular enclosure and the sound enters through a small hole in the enclosure's top surface. A numerical model is presented to predict the variation in the sound field with position within the enclosure. An objective of this study is to determine up to which frequency the pressure distribution remains sufficiently uniform so that a pressure calibration can be made in free space. The secondary motivation for this effort is to facilitate microphone design by providing a means of predicting how the placement of the microphone diaphragm in the package affects the sensitivity and frequency response. While the size of the package is typically small relative to the wavelength of the sounds of interest, because the dimensions of the package are on the order of the thickness of the viscous boundary layer, viscosity can significantly affect the distribution of sound pressure around the diaphragm. In addition to the need to consider viscous effects, it is shown here that one must also carefully account for thermal conductivity to properly represent energy dissipation at the system's primary acoustic resonance frequency. The sound field is calculated using a solution of the linearized system consisting of continuity equation, Navier-Stokes equations, the state equation and the energy equation using a finite element approach. The predicted spatial variation of both the amplitude and phase of the sound pressure is shown over the range of audible frequencies. Excellent agreement is shown between the predicted and measured effects of the package on the microphone's sensitivity.

Keywords

microphone; packaging; acoustic; finite element

1 Introduction

MEMS technology has enabled the development of low-cost miniature microphones that are well-suited to manufacturing processes currently used in portable electronic products. These microphones normally include a silicon chip containing a pressure sensitive diaphragm, and

suitable read-out electronic circuitry enclosed in a package designed to protect it from fabrication or environmentally-induced damage. The protective package typically consists of a small box with a hole for sound to enter. A circuit board normally comprises one of the six sides of the box, which contains the microphone chip and supporting electronics.

Calibration of the pressure sensitivity of a microphone in this configuration is problematic. The pressure sensitivity, by definition, is the response of a microphone to a uniform pressure over the surface of the active element, in this case the MEMS chip. The pressure sensitivity relates to the theoretical design of a microphone, and is the appropriate sensitivity (as opposed to the free-field sensitivity) when the microphone is located in an infinite baffle or in a small enclosure.

Current calibration methods for the pressure sensitivity of MEMS microphones based on electrostatic actuation are not applicable. The electrostatic actuator requires access for the placement of an electrode very close to the chip. Even if this were physically possible, the attendant fringe capacitance would prohibit the needed excitation of the diaphragm[Measurement(2004)]. The coupler method limits the calibration to relatively low frequencies due to the excitation of coupler modes[Methods(2001)]. Calibration of the pressure sensitivity by a free-field method[Values(2006), Zuckerwar et al(2006) Zuckerwar, Herring, and Elbing], on the other hand, is possible if the interior pressure within the MEMS package remains nearly uniform. At sufficiently low frequencies, sound entering the access hole will reveal a nearly uniform pressure distribution within the interior of the package. The purpose of this work, then, is to determine the conditions, especially the limiting frequency, under which the pressure at the chip position remains nearly uniform. The analysis further permits determination of the optimal position for a uniform interior pressure distribution over the surface of the chip.

In addition to concerns about the proper calibration of MEMS microphones, the package consisting of a small enclosure containing a sound inlet port possesses all of the needed geometry to create a Helmholtz resonance where the air-filled volume comprises a compliance and the air in the port constitutes a mass with viscous damping. An aim of this study is to estimate the influence of the Helmholtz resonance on the detected pressure.

2 MEMS microphone configurations

In current MEMS microphones, there are two general types of packages available and they have very different influences on the microphone's performance. In the first, the microphone chip and the electronics components are placed on a small circuit board comprising the floor of the package[Loeppert and Lee(2006)]. A small five-sided rectangular box is then placed over the circuit board that has a sound inlet hole in its top as shown in Fig. 1(a). The microphone chip contains a pressure sensitive diaphragm that detects the difference in pressure between the air within the enclosure and the air in the small backvolume behind the diaphragm. The size of this backvolume is normally determined by the thickness of the microphone chip.

A second type of microphone package differs from the first in that the sound inlet hole is now placed underneath the microphone chip rather than on the top of the package as shown in Fig. 1 (b). The assembly is described in detail by [Dehé(2007)]. In this case, the microphone diaphragm responds to the difference in pressure between the exterior of the sound inlet hole and the interior of the package. The entire package then serves as the backvolume for the diaphragm. This assembly has advantages over the first in that the overall height of the package can be reduced and the microphone's sensitivity can be improved owing to the reduced air stiffness of the larger backvolume.

Since both types of microphone packages consist of a box with a sound inlet hole, they both behave as Helmholtz resonators and consequently have marked influences on the frequency response of the microphone. An important goal of this paper is to examine the effects of the first type of package on the microphone's frequency response and to examine the sensitivity as a function of the position of the diaphragm within the volume.

Because the enclosure is small relative to the sound wavelength, in previous studies it has been assumed that the pressure is fairly uniform within the volume so that the microphone's sensitivity has been expected to not vary significantly with the position of the sensor in the package. [Winter et al(2010) Winter, Feiertag, Leidl, and Seidel] has analyzed the influence of the second type of package (shown in Fig. 1(b)) on the frequency response of a MEMS microphone using an equivalent circuit approach. This lumped-parameter model provides considerable insight into the parameters that affect the frequency response in these systems. Excellent agreement between measurements and predictions is shown for the microphone without a package included. When the effects of the package are accounted for, the model provides reliable estimates of the passband sensitivity and the frequency of the Helmholtz resonance. The amount of energy dissipation in the packaged microphone appears more challenging to estimate so the amount of amplification at resonance was not predicted as successfully as the passband sensitivity. A similar problem was reported by A. Kärkkäinen, L. Kärkkäinen, J. Cozens, M. Malinen and P. Raback in [Kärkkäinen et al(2004) Kärkkäinen, Kärkkäinen, Cozens, Malinen, and Raback] where the authors compared the measured and simulated quality factors of the source impedance resonance peaks in a small system with two cavities and a tube. They found that the measured value of the air viscosity is double the correct value and concluded that there is an unaccounted loss mechanism in the measurement.

The task of calculating the amplification due to the package at resonance is addressed in the present study. In the design considered here, it is shown that by accounting for both viscous and thermal effects in the system it is possible to obtain excellent agreement between calculated and measured results at all frequencies of interest, including those near resonance.

While lumped parameter models provide excellent insight into the parameters that affect performance as in [Winter et al(2010) Winter, Feiertag, Leidl, and Seidel], they are not as useful when an estimate of the spatial dependence of the pressure within the package is needed. This is a focus of the present investigation where the effect of the placement of the microphone chip in the package of Fig. 1(a) is considered. In addition, because the dimensions of the interior of the package are on the order of the thickness of the viscous boundary layer in air (less than 1 mm for most frequencies) it is likely that viscous and/or thermal effects could have a non-intuitive influence on the spatial distribution of the pressure. Knowing the pressure at the input sound port, it is not a simple matter to reliably estimate the sound pressure incident across the microphone diaphragm.

In order to account for the diminutive size of the acoustic space in the microphone package, a finite element model has been constructed that accounts for the usual acoustic effects in the fluid along with dynamic viscosity and heat conduction. The distribution of the sound field within the package is calculated for a given pressure at the sound inlet hole. Measurements of the output of a Knowles MEMS microphone with and without the effects of the package are then compared with those obtained from the finite element model.

As Lighthill pointed out as early as 1957 [Alblas(1961)], the influence of viscosity and heat conductivity in the propagation of sound waves are of the same order of magnitude. Therefore it is imperative that the effects of heat conduction be accounted for in analyses of viscous diffraction problems in acoustics.

The results presented here indicate that at frequencies that are away from resonance, when viscous effects are accounted for in the analysis, the present approach enables one to calculate the distribution of the sound pressure within the package and can hence provide guidance on where to place the pressure sensor in the enclosure. It is also shown that frequencies near the Helmholtz resonance of the package, in addition to accounting for viscosity, it is also necessary to include the effects of thermal conduction in order to properly calculate the amplitude of the resonant response.

3 Frequency domain sound propagation equations including viscothermal losses

In many acoustical devices micromachined using MEMS technology the linear dimensions of the microsensors are comparable to the viscous boundary-layer thickness of the air domain. As a consequence, viscous effects (losses) can have a marked influence on the distribution of the sound field within and around the components of the device. In many cases the resulting Visco Acoustical Theory gives results in good agreement with the measurements. Results presented here indicate that in analyzing the acoustic effects of the package of a MEMS microphone, considering viscosity without heat conduction provides a reliable description of the pressure field at all frequencies except near resonance. At resonance, the calculated pressure is found to exceed the measured value by approximately nine decibels. An analysis that carefully accounts also for thermal conductivity is found to provide extremely close agreement between predictions and measurements for all frequencies.

3.1 General viscothermal regime

In the system studied here, a harmonically oscillating temperature creates a thermal wave which at the resonant frequency has a thermal boundary layer slightly larger than the viscous boundary layer. Therefore, both the thermal conductivity as well as the air viscosity have to be included in the analysis to proper account for the interactions of the sound wave with these miniature structures. Hence, the starting point in approaching the sound wave behavior of the miniature silicon devices has to include the following equations [Alblas(1961)], [Beltman(1999)]:

(a) the continuity equation

$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{V} = 0, \quad (1)$$

(b) the momentum (Navier-Stokes) equation

$$\rho \frac{d\mathbf{V}}{dt} + \nabla \cdot \boldsymbol{\sigma} = 0, \quad (2)$$

(c) the state equation for an ideal gas

$$P = R_0 \rho T, \quad (3)$$

(d) the energy equation

$$\rho C_p \frac{dT}{dt} = \nabla \cdot (k \nabla T) + \frac{dP}{dt} + \Phi(\mu, \mu_B, \mathbf{V}). \quad (4)$$

Here by $\mathbf{V}$ we denote the particle velocity, ρ is density, P the pressure and T the temperature and d/dt denotes the material time derivative

$$\frac{dT}{dt} = \left(\frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla \right) T. \quad (5)$$

The stress tensor σ has the components

$$\sigma_{ij} \equiv \sigma_{ij}[P, \mathbf{V}] = \left[\mathbf{P} - \left(\mu_B - \frac{2}{3} \mu \right) \nabla \cdot \mathbf{V} \right] \delta_{ij} - \mu \left(\frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_i} \right), \quad (6)$$

and the dissipation function Φ can be written as

$$\Phi(\mu, \mu_B, \mathbf{V}) = \sum_{i,j=1}^3 (\sigma_{ij} - \mathbf{P} \delta_{ij}) \frac{\partial V_i}{\partial x_j}. \quad (7)$$

Also, μ and μ_B are the shear and bulk viscosities, R_0 is the universal gas constant C_p the specific heat at constant pressure and k the gas conductivity, all of them supposed constants.

Equations (1), (2), (3) and (4) will be linearized by considering the dependent variables to be small perturbations about the static state of the fluid, given by ρ_0 , p_0 , T_0 and $\mathbf{V}_0 = 0$. In the case of time-harmonic oscillations of angular frequency $\omega = 2\pi f$ (f being the frequency in Hertz) we can write

$$\rho = \rho_0 + \rho' e^{i\omega t} \quad (8)$$

$$P = p_0 + p' e^{i\omega t} \quad (9)$$

$$T = T_0 + T' e^{i\omega t} \quad (10)$$

$$\mathbf{V} = \mathbf{v}' e^{i\omega t} \quad (11)$$

$\rho' e^{i\omega t}$, $p' e^{i\omega t}$, $T' e^{i\omega t}$ and $\mathbf{v}' e^{i\omega t}$ being the perturbations of the basic quantities. The case of the general time dependence can be obtained after analyzing each frequency separately by Fourier superposition. This gives the frequency domain viscothermal equations describing the propagation of the sound waves with viscous and thermal losses in the form

$$\nabla \cdot \mathbf{v}' + i\omega \frac{\rho'}{\rho_0} = 0 \quad (12)$$

$$\mu \nabla^2 \mathbf{v}' - i\omega \rho_0 \mathbf{v}' - \nabla p' + \left(\frac{\mu}{3} + \mu_B \right) \nabla (\nabla \cdot \mathbf{v}') = 0 \quad (13)$$

$$\frac{p'}{p_0} = \frac{\rho'}{\rho_0} + \frac{T'}{T_0} \quad (14)$$

$$\nabla (k \nabla T') + i\omega (p' - \rho_0 C_p T') = 0 \quad (15)$$

The relationships (12)-(15) represent a system of equations for determining all the perturbation quantities. Equation (14) is algebraic and can be used for determining the density perturbation in terms of pressure and temperature perturbations. This can be substituted into equation (12) such that the continuity equation will be written in linearized form as:

$$\nabla \cdot \mathbf{v}' + i\omega \left(\frac{p'}{p_0} - \frac{T'}{T_0} \right) = 0 \quad (16)$$

Further on, the velocity field can be eliminated between equation (13) and (16) resulting in another thermodynamic equation involving only the pressure and temperature perturbation fields

$$\nabla^2 p' + i\omega \left(\frac{4\mu}{3} + \mu_B \right) \nabla^2 \left(\frac{p'}{p_0} - \frac{T'}{T_0} \right) + \rho_0 \omega^2 \left(\frac{p'}{p_0} - \frac{T'}{T_0} \right) = 0 \quad (17)$$

Equations (15) and (17) can be viewed as a system of two partial differential equations (PDE) for determining the pressure and temperature perturbations. However, the classical acoustical boundary condition for the pressure on hard surfaces

$$\frac{\partial p'}{\partial n} = 0 \quad (18)$$

applies only in the case of inviscid gas. In the case of accounting for gas viscosity this condition has to be replaced by the aerodynamic condition claiming no-slip of air particles on solid boundaries

$$\mathbf{v}' = 0 \quad (19)$$

associated with the given values of the temperature perturbation on solid surfaces. On the surface of the acoustical port the normal stress (having as its main component the pressure) is given. Likewise, the tangential stress and the thermal flux cancel out.

The result of this analysis shows that in the case of viscothermal acoustics the main unknown variables are the pressure, temperature and velocity perturbations and the PDE system to be solved consists of equations (13), (15) and (16).

3.2 The adiabatic regime for an inviscid gas

In some particular thermodynamic regimes the number of dependent variables can be decreased. Thus, when the gas thermal conductivity k is small (cancels out) the thermal exchanges between gas particles can be neglected which characterize the adiabatic regime [Zuckerwar(1995)], [Zuckerwar(1997)]. In this case, the energy equation (15) yields the pressure perturbation as

$$T' = \frac{p'}{\rho_0 C_p} \quad (20)$$

Equation (17) becomes the wave equation for the pressure perturbation

$$\nabla^2 p' + k_0^2 p' = 0 \quad (21)$$

where the adiabatic speed of sound c_0 is defined by

$$c_0 = \left[\frac{\rho_0}{p_0} - \frac{1}{C_p T_0} \right]^{-1/2} \quad (22)$$

and the adiabatic wave number is

$$k_0 = \frac{\omega}{\sqrt{c_0^2 + i\omega(4\mu/3 + \mu_B)/\rho_0}} \quad (23)$$

The PDE (21), completed with the boundary condition (18) on solid surfaces, and the assigned value of the pressure at the opening are sufficient conditions for obtaining the pressure inside the cap in the case where the viscosity of the gas can be neglected (inviscid gas).

3.3 The adiabatic regime for a viscous gas

According to the previous discussion, the pressure equation (21) is of little use in the viscous case due to the missing of a boundary condition for pressure. Correspondingly, for determining the four dependent variables: the perturbation pressure p' and the velocity field $\mathbf{v}$ (three components) the linearized Navier-Stokes equations (13) and the linearized continuity equation (16) will be used associated with no slip boundary conditions on solid surfaces (19).

4 Computational Methodology

4.1 The case of adiabatic regime for a viscous gas

As will be shown in the following, the model of the adiabatic regime for a viscous gas was found to be appropriate for understanding the effect of port position on the microphone sensitivity except for a very small frequency band around resonance. Thus, the frequency domain linearized Navier-Stokes and continuity equation (13), (16) were implemented in the commercial finite element method code, COMSOL Multiphysics v.3.5. A finite element model has been constructed to examine the sound pressure distribution within the package of a MEMS microphone due to an imposed pressure at the mouth of the sound inlet orifice. Two configurations have been considered: one having off-center hole and a second cap

having the sound inlet orifice in the center. A mesh of unstructured tetrahedral elements using *Lagrange* – P_2P_1 interpolation polynomials with a regular refinement at the mouth of the sound inlet was used. All the numerical work has been performed on a workstation having 24 cores at 2.93GHz, and 96 Gbyte RAM. The typical time required to obtain solutions at each frequency was around 50 seconds. The models contained 123,295 to 301,957 degrees of freedom.

4.1.1 Analysis of a cap with an off-center hole—The assumed geometry of the package is shown in Fig. 1(a). The finite element model used here neglects the acoustic effects of the MEMS chip and the preamplifier. These effects could be included by modifying the geometry of the model; the only impact on the calculations would be to increase the time required to obtain solutions if the model requires additional degrees of freedom.

The air density used in the computations was $1.21 \text{ [kg/m}^3\text{]}$, the dynamic viscosity was taken to be $1.82 \times 10^{-5} \text{ [Pa}\cdot\text{s]}$ and the speed of sound was 340 [m/s] . Fig. 2 shows the predicted pressure distribution on the surface of the package due to a 1 Pa pressure applied at the sound inlet orifice for a frequency of 5 kHz. The maximum pressure amplitude in the volume is estimated to be 1.195 Pa at the end opposite the sound inlet. The distribution of the predicted pressure within the cavity has been found to vary by approximately 20% along its length. However, variations across the width of the package are comparatively small, as shown in Fig. 3. For this reason, in the following figures only the variation of the relative pressure with respect to x (the length direction) will be presented along the symmetry line at the bottom of the cavity.

The effect of frequency on the distribution of the pressure along the centerline of the bottom of the cavity is shown in Figs. 4 and 5. In the following figures, the calculated pressure is determined over the normal frequency range of the MEMS microphone, from 100Hz-10,000Hz. Fig. 4 shows the pressure on a decibel scale as a function of position. The figures show that at the highest frequency used here, the pressure varies within the cavity by approximately 4 dB. Fig. 5 shows the phase of the pressure relative to that imposed at the sound inlet. Finally, Fig. 6 shows the pressure deviation from the mean pressure along the same symmetry line for the range of frequencies 1kHz-10kHz.

4.1.2 Analysis of a cap having the inlet orifice located at the center of the package—In the case where the inlet hole is placed at the center of the upper plane surface, the air domain has two symmetry planes and it is sufficient to analyze only a quarter of the structure. The origin of the system of coordinates will be placed at the center of the floor of the package. Fig. 7 shows the pressure in decibels as a function of position on the floor of the microphone package due a unit applied pressure at the opening. Fig. 8 shows the phase of the pressure in radians as a function of position on the floor of the microphone cap due again to a 1 Pa pressure applied at the inlet. Finally, Fig. 9 shows the pressure deviation from the mean value along the symmetry line of the floor of the cap for a range of frequencies between 1kHz and 10kHz.

4.2 Comparison with the case of adiabatic inviscid gas

All the above results were obtained by solving the linearized Navier-Stokes and continuity equations in the frequency domain including, therefore, the effect of viscosity. In order to see the importance of viscosity on the acoustic response of this system, results are also shown in Fig. 7 where viscosity has been neglected (empty symbols). As expected, in the frequencies near resonance, the predicted pressure within the enclosure is substantially higher if viscosity is neglected.

4.3 The general viscothermal regime

As can be seen from 10, at frequencies different from those close to resonance, the viscous adiabatic model is appropriate to describe the effect of port position on sensitivity. However, at resonance the calculated pressure exceeds the measured value by nine decibels. To obtain a more accurate model of the pressure at resonance, the thermal loss has to be considered along with viscous effects which defined the general viscothermal regime. Therefore, the system of linearized equations solved in this case consists of the complete system of equations (13), (15) and (16) the dependent variables being the pressure, temperature and velocity perturbations. The parameters used for the air in this model were: $k = 2.6 \times 10^{-2} [W/(m \cdot K)]$, $T_0 = 293 [^\circ K]$, $C_p = 1006 [J/(kg \cdot K)]$. As the determination of temperature perturbation involves an iterative process, the calculations are more time-consuming than those of the adiabatic cases. From the computational point of view, the system of linearized equations of the viscothermal regime was implemented in the Fluid Thermal Interaction software of COMSOL Multiphysics 3.5. The new model gives excellent agreement between the measured and predicted results for all frequencies (including the resonant frequency) the price paid for this being an increase in computation time.

5 Comparison with some measured results

Fig. 10 shows the gain due to the cover on the sound pressure detected by the microphone diaphragm. The measured data were obtained by using the electronic output of the microphone with and without the protective cover in place. The difference in the output signals (in decibels) is shown as a function of frequency. The predicted results were obtained using the finite element model described above. Predicted results are shown both with and without the effects of thermal conductivity included in the model. The figure shows excellent agreement between the measured and predicted results when thermal conductivity is included. A significant resonant amplification due to the cover is evident at approximately 14 kHz. The amplitude of this resonant amplification is overpredicted when thermal effects are not included. Since the response at resonance is determined by energy dissipation, these results suggest that to properly account for dissipation, models of the response of miniature microphones such as that considered here should include the effects of thermal conduction along with viscous losses.

6 Conclusions

For a prescribed sound pressure incident on the acoustic inlet hole of the MEMS microphone package studied here, the sound field within the enclosure is predicted to vary by about 4dB with position at high frequencies (10kHz). The pressure within the package due to an imposed sound field at the sound inlet hole can be estimated with reasonable accuracy using a finite element-based solution of the frequency domain Navier-Stokes equations completed with continuity equation for all frequencies except at a very small band around resonance frequency of the package. To accurately determine the resonant amplification due to the package, the model has to be completed by adding the equations involving the effect of thermal conduction of the air as was predicted by Lighthill many years ago.

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References

- Alblas J. On the diffraction of sound waves in a heat-conducting viscous medium. *Koninkl Ned Akad Wetenschap Proc B*. 1961; 64:351–367.
- Beltman W. Viscothermal wave propagation including acousto-elastic interaction, part i: theory. *Journal of Sound and Vibration*. 1999; 227(3):555–586.
- Dehé A. Silicon microphone development and application. *Sensors and Actuators A: Physical*. 2007; 133(2):283–287.
- Kärkkäinen A, Kärkkäinen L, Cozens J, Malinen M, Raback P. Fem simulations of thermal and viscous boundary effects in acoustics. *Proceedings of the International Congress on Acoustics*. 2004:V3635–V3638.
- Loeppert, P.; Lee, S. Sisonic—the first commercialized mems microphone. *Solid-State Sensors, Actuators and Microsystems Workshop*; Hilton Head Island, South Carolina. 2006. p. 27-30.
- CEI/IEC 61094-6 Measurement microphones - Part 6: Electrostatic actuators for determination of frequency response. *International Electrotechnical Commission*; Geneva: 2004. Measurement.
- CEI/IEC 61094-5 Methods for pressure calibration of working standard microphones by comparison. *International Electrotechnical Commission*; Geneva: 2001. Methods.
- CEI/IEC 61094-7 Values for the difference between free-field and pressure sensitivity levels of laboratory standard microphones. *International Electrotechnical Commission*; Geneva: 2006. Values.
- Winter M, Feiertag G, Leidl A, Seidel H. Influence of a chip scale package on the frequency response of a mems microphone. *Microsystem Technologies-Micro-and Nanosystems-Information Storage and Processing Systems*. 2010; 16(5, Sp. Iss. SI):809–815.10.1007/s00542-009-0994-z
- Zuckerwar A, Herring G, Elbing B. Calibration of the pressure sensitivity of microphones by a free-field method at frequencies up to 80 khz. *The Journal of the Acoustical Society of America*. 2006; 119:320. [PubMed: 16454287]
- Zuckerwar, AJ. Principles of operation of condenser microphones. In: Wong, GSK.; Embleton, TFW., editors. *AIP Handbook of Condenser Microphone: Theory, Calibration and Measurements*. AIP; 1995. p. 37-69.
- Zuckerwar, AJ. Speed of sound in fluids. In: Crocker, MJ., editor. *Encyclopedia of Acoustics*. Vol. 1. John Wiley & Sons; 1997. p. 69-79.

Fig. 1. Schematics of two MEMS microphone packages. The microphone and amplifier chips are mounted to a circuit board and enclosed in a box. In (a) the sound enters the enclosure through a hole in the top. In (b) the sound enters through the underside of the microphone chip. The configuration shown in (a) is examined in the present study.

Fig. 2.
(Color online) The predicted pressure distribution in the air domain corresponding to the protective package of the MEMS microphone. The figure shows the pressure on the surface obtained by solving the frequency-domain Navier-Stokes boundary value problem using the finite element program at a frequency $f=5$ kHz.

Fig. 3. (Color online) The predicted pressure (p) distribution along the bottom of the cavity ($z=0$) at the frequency $f=5$ kHz. The dependence of the pressure on the position across the width of the package (the y direction) is relatively weak compared to the variation along the length (the x direction).

Fig. 4.
(Color online) The magnitude of the relative pressure $|p/p_i|$ in decibels versus distance x along the floor of the package for frequencies $f = 0.1$ kHz, to $f = 10$ kHz for the case of an off-centered hole. Note that in the system considered in this study, the microphone diaphragm resides from approximately $x = 4.36$ mm to $x = 5.06$ mm.

Fig. 5.
(Color online) The phase of the relative pressure p/p_i versus distance x along the floor of the package for frequencies $f = 0.1$ kHz, to $f = 10$ kHz for the case of an off-centered hole.

Fig. 6.
(Color online) Pressure deviation from the mean pressure along the symmetry line at the floor of the package for the range of frequencies 1kHz-10kHz for the case of an off-centered hole.

Fig. 7.

(Color online) Pressure in decibels as a function of position on the floor of the microphone package due a unit applied pressure at the opening for the case of a centered hole. Data with empty symbols were obtained by neglecting the effects of viscosity. The predicted pressure is substantially higher when viscosity is neglected in comparison to results obtained when viscosity is included (filled symbols).

Fig. 8.
(Color online) Phase of the pressure in radians as a function of position on the floor of the microphone cap due to a 1 Pa pressure applied at the inlet for the case of a centered hole.

Fig. 9.
(Color online) Pressure deviation from the mean value along the symmetry line on the floor of the cap for a range of frequencies between 1kHz and 10kHz for the case of a centered hole.

Fig. 10.

(Color online) Effect of the cover on microphone sensitivity. The sensitivity of the microphone is increased significantly at high frequencies due to the acoustic resonance in the cover. Predicted results based on a model that includes both viscous and thermal effects show excellent agreement with measurements at all frequencies. Predictions that do not account for thermal effects (FEM viscoacoustical model) do not agree as well with measurements at resonance.