Influence of air masses on microphone vibration sensitivity

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1 Microphones and acceleration



Figure 1: A MEMS condenser microphone. The condenser consists of a compliant diaphragm (solid line) and rigid back plate (dashed line). The ASIC produces a voltage signal (not shown) proportional to the effective displacement of the diaphragm relative to the back plate.

Capacitive microphones are sensitive to both acoustic pressure and mechanical acceleration, because both will tend to cause the displacement of a microphone's diaphragm relative to its back plate. A MEMS microphone with diaphragm and back plate are shown in Figure 1. The diaphragm is a thin, flexible membrane connected to the microphone package at its edges. The effective (spatial average) displacement of the diaphragm relative to the back plate, in meters, is

$$\Delta l(t) = d_d(t) - d_0(t) \tag{1}$$

where $d_d(t)$ is the effective displacement of the diaphragm and $d_0(t)$ is the displacement of the microphone package, which the back plate is rigidly connected to. The ASIC produces a voltage

$$u(t) = S_e \Delta l(t) \tag{2}$$

where S_e (V/m) is the electronic sensitivity of the microphone. The two causes of $\Delta l(t)$ are illustrated in Figure 2. The force due to an acoustic pressure on the diaphragm compresses the inside air axially (assuming that the microphone is stationary), and the electronics produce a voltage u(t). This voltage can represent the pressure measured by the microphone. If the microphone accelerates, the force required to accelerate the effective mass of the diaphragm axially compresses the air inside, from which the electronics produce an unwanted voltage which also appears in u(t).

We will assume that all vibration accelerates the microphone axially, normal to the plane of the diaphragm. An examination of the sensitivity to vibration in other directions (as well as rotation) is left for future studies. Vibration of surfaces nearby to the microphone may cause pressure which contributes to u(t), and must be considered in product designs that minimize unwanted vibration signals. For example, when the exterior surface of a laptop which houses a microphone inlet vibrates, it will radiate undesired sound pressure that the microphone picks up. The topic of this work will be the voltage sensitivity to vibration of a microphone on its own, and not as part of a larger product (such as a laptop). Any sources of pressure that are caused by vibration external to the microphone itself will therefore be neglected in this work.



Figure 2: The diaphragm moves relative to the rest of the microphone when (Top:) acoustic pressure impinges on the diaphragm, or (Bottom:) the microphone's outer structure accelerates. In both cases, the diaphragm is displacing relative to the back plate (not shown) because it is rigidly fixed to the rest of the microphone.

The undesired sensitivity to vibration in microphones has been described as far back as the 1960s. Vibration noise in hearing aids was described with both external causes (the walking motion of the user) and internal causes (the mechanical vibration of the speaker). Friis observes [1] that internal feedback, including vibration response, has become a greater

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concern in hearing aid designs due to decreasing design size of hearing aids. Many newer electronic products such as laptops, cell phones, and smart appliances all operate in vibrations of both internal and external causes. De Oliveira describes [2] acceleration of the microphone in a smart speaker. This microphone undergoes vibration when the speaker is producing sound, which may affect the 'barge-in' performance; whether the smart speaker can still recognize a trigger while it is producing sound. For example, De Oliveira states, the vibration signal from the microphone may saturate the smart speaker's echo cancellation, rendering it less able to recognize a voice from far away.

The main purpose of the present work is to study the pressure related acceleration sensitivity that is caused by the bodies of air inside of a microphone.

We use a transfer matrix formulation that treats the microphone as a one-dimensional duct. This duct can have an arbitrary number of straight pipes and area discontinuities, allowing for complex geometry. The effects of acoustic pressure due to nearby radiating surfaces is neglected. We will demonstrate that the pressure related acceleration sensitivity of a sub-miniature microphone may be approximated by a simple function of axial length of the bodies of air it contains.

2 Pressure related acceleration sensitivity

Consider a microphone that is sensitive to a harmonic pressure p(t) (Pa) and acceleration a(t) (m/s²). These excitations are represented by their complex amplitudes, P(f) and A(f)in the expressions

 $p(t) = \operatorname{Re}\left\{P(f)e^{i2\pi ft}\right\}$ (3)

and

$$a(t) = \operatorname{Re}\left\{A(f)e^{i2\pi ft}\right\}.$$
(4)

The microphone's signal voltage U(f) (V) is the sum of two components

$$U(f) = U_p(f) + U_a(f) \tag{5}$$

where $U_p(f)$ (V) is the pressure component, and $U_a(f)$ (V) is the acceleration component. Each component has its own linear time invariant sensitivity function [3]:

$$U_p(f) = P(f)S_p(f) \tag{6}$$

and

$$U_a(f) = A(f)S_a(f) \tag{7}$$

where $S_p(f)$ (V/Pa) is the microphone's sensitivity to pressure and $S_a(f)$ (V/m/s²) is the microphone's sensitivity to acceleration. We can rewrite (5) using (6) and (7)

$$U(f) = P(f)S_p(f) + A(f)S_a(f)$$
(8)

The magnitude of S_a is not a good indicator of acceleration performance on it's own. For example, S_a could be reduced to zero by simply eliminating S_e , the electronic sensitivity of the microphone, which would have the undesired effect of also

eliminating S_p . When S_a is normalized to S_p , we obtain the (Pa/(m/s²)) pressure-related acceleration sensitivity

$$P_a(f) = \frac{S_a(f)}{S_p(f)} \tag{9}$$

which we will use to quantify the acceleration performance, as it is independent of any factors that S_p and S_a have in common, such as S_e .

3 Analytical models

In the following we will show that the expression for P_a when a microphone acts like a spring mass damper does not depend on the spring stiffness or the damping coefficient. We will produce expressions for P_a which account for the acoustic fields inside of several microphone geometries, and show that each of them is roughly proportional to the lengths of the bodies of air each microphone contains.

3.1 Single degree of freedom model



Figure 3: Lumped parameter mechanical model of the microphone. The voltage signal of the microphone (not shown) is a function of $d_d(t) - d_0(t)$.

Ignoring the effects of a pressure-equalizing port, assume that a microphone's mechanical sensitivity can be approximated by the linear second order oscillator shown in Figure 3 [4]. The sensitivity to pressure is

$$S_p(f) = S_e \frac{s_d}{k + i2\pi fc - (2\pi f)^2 m_d}$$
(10)

where m is the effective mass of the diaphragm (kg), k is the effective spring constant (N/m), c is the effective damping coefficient (N · s/m) s_d is the area of the diaphragm. The sensitivity to acceleration is

$$S_a(f) = S_e \frac{m_d}{k + i2\pi fc - (2\pi f)^2 m_d}$$
(11)

Using (9), the pressure related acceleration sensitivity is

$$P_a(f) = \frac{m_d}{s_d} \tag{12}$$

Rule *et al.* [5] obtain this same relationship by observing that the acceleration of a diaphragm must be proportional to some pressure equal to that diaphragm's mass per unit area (m_d/s_d) .

3.2 An ideal microphone

The mass per unit area of a diaphragm is proportional to the thickness. The thickness of a micromachined silicon MEMS diaphragm can be extremely small, less than 1 micrometer [6]. Given a silicon density of 2330 kg/m^3 , this compares to a 2 mm long body of air. This mass moves with the diaphragm, contributing significantly to P_a .

Consider an ideal microphone with a diaphragm so thin that its mass per unit area is negligible. Inside this microphone, the air is an acoustic body (Figure 4) and the diaphragm moves according to the motion of the air that touches it. If the acoustic pressure and velocity are a function of axial position (p(x,t) and u(x,t)), the one-dimensional acoustic pressure and momentum relationships can be used. The acoustic body in Figure 5 represents a microphone with



Figure 4: One dimensional model of a microphone. Solutions to the acoustic wave equation in one dimension have incident wave $p_i(x, t)$ and reflected wave $p_r(x, t)$.

a massless diaphragm at $x = L_1$. At the bottom of the body, the acoustic pressure and velocity at the microphone's base are $P_0(f)$ and $U_0(f)$. At the top of the body, the acoustic pressure and velocity on the diaphragm are $P_d(f)$ and $U_d(f)$. This microphone satisfies the transfer matrix relationship [4]:



Figure 5: The microphone of Figure 4. A transfer matrix T defines the relationship between (P_d, U_d) and (P_0, U_0) for a single uniform duct element [7].

$$\begin{pmatrix} P_d(f)\\ U_d(f) \end{pmatrix} = [\mathbf{T}]_{2 \times 2} \begin{pmatrix} P_0(f)\\ U_0(f) \end{pmatrix}$$
(13)

where $[T]_{2\times 2}$ is the (frequency dependent) transfer matrix for a straight pipe that satisfies the one-dimensional acoustic model [7].

The microphone's signal (2) is

$$U(f) = \frac{1}{2i\pi f} S_e(U_d(f) - U_0(f))$$
(14)

where we've taken the integrals

$$D_d(f) = \frac{U_d(f)}{2i\pi f} \tag{15}$$

and

$$D_0(f) = \frac{U_0(f)}{2i\pi f} \tag{16}$$

The pressure sensitivity is defined by (13) when $U_0(f) = 0$

$$S_p(f) = S_e \frac{T_{21}}{i2\pi f T_{11}} \tag{17}$$

The acceleration sensitivity is defined when $P_d(f) = 0$

$$S_a = -\frac{S_e}{(2\pi f)^2} \left(-\frac{T_{12}T_{21}}{T_{11}} + T_{22} - 1 \right)$$
(18)

The pressure related acceleration sensitivity (9) is

$$P_a(f) = -\frac{\rho_0 \cos(kL_1) - 1}{k \sin(kL_1)}$$
(19)

where ρ_0 is the density of the air and $k = 2\pi f/c$ is the wavenumber. At low frequencies, $P_a(f)$ is approximately equal to the first term of its Taylor series, which is not frequency dependent:

$$P_a \approx \rho_0 \frac{L_1}{2} \tag{20}$$

as seen in Figure 6.



Figure 6: The back volume (Figure 5) transfer matrix model agrees with the Taylor approximation (Eq. 20), which is a simple function of the microphone's length.

3.3 Including a front volume

Using an additional duct element, Figure 7 includes a front volume. The transfer matrix relating the base to the inlet [T] is

$$[\boldsymbol{T}] = [\boldsymbol{F}][\boldsymbol{B}] \tag{21}$$

where [B] is the back volume transfer matrix and [F] is the front volume transfer matrix. The motion of the diaphragm satisfies

$$\begin{pmatrix} P_i \\ U_i \end{pmatrix} = [\mathbf{T}]_{2 \times 2} \begin{pmatrix} P_0 \\ U_0 \end{pmatrix}$$
(22)



Figure 7: The microphone of Figure 4, with an additional element representing a front volume. A transfer matrix T may be obtained from transfer matrices representing the front and back volumes.

and

$$\begin{pmatrix} P_d \\ U_d \end{pmatrix} = [\boldsymbol{B}]_{2 \times 2} \begin{pmatrix} P_0 \\ U_0 \end{pmatrix}$$
(23)

The pressure sensitivity is defined by (22) and (23) when $U_0(f) = 0$

$$S_p = S_e \frac{B_{21}}{T_{11}i2\pi f}$$
(24)

The acceleration sensitivity is defined when $P_d(f) = 0$

$$S_a = -\frac{S_e}{(2\pi f)^2} \left(-B_{21} \frac{T_{12}}{T_{11}} + B_{22} - 1 \right)$$
(25)

Since [B] and [F] are uniform ducts, the pressure related acceleration sensitivity (9) is

$$P_a = -\rho_0 \frac{\cos(k(L_1 + L_2)) - \cos kL_2}{k\sin kL_1}$$
(26)

Or, at low frequencies,

$$P_a \approx \frac{\rho_0}{2} (L_1 + 2L_2) \tag{27}$$

A comparison between the exact solution and the low frequency estimate is shown in Figure 8.

3.4 Non-uniform cross section

We will show that the dependence on length in (27) still stands for microphones with non-uniform cross sections illustrated in Figure 9. The transfer matrices [B] and [F] can be chosen based on the back and front volume geometry that we want to consider. We will ignore thermoviscous effects, in Section 4 we will see that the effect on P_a is small. A small diaphragm and a tube are represented by discontinuities in the area of the duct model. The horizontal surfaces move with the microphone and displace air as shown in Figure 10 The transfer matrix relationship for this duct element is

$$\begin{pmatrix} P_{n+1} \\ U_{n+1} \end{pmatrix} = [\boldsymbol{J}] \begin{pmatrix} P_n \\ U_n \end{pmatrix} + [\boldsymbol{S}] \begin{pmatrix} P_0 \\ U_0 \end{pmatrix}$$
(28)

where

$$\begin{bmatrix} \mathbf{J} \end{bmatrix} = \begin{bmatrix} 1 & 0\\ 0 & s_n/s_{n+1} \end{bmatrix}$$
(29)

satisfies volume velocity for the stationary element and

$$\begin{bmatrix} \mathbf{S} \end{bmatrix} = \begin{bmatrix} 0 & 0\\ 0 & 1 - s_n/s_{n+1} \end{bmatrix}$$
(30)



Figure 8: The back and front volume (Figure 7) transfer matrix model agrees with the Taylor approximation (27).



Figure 9: A microphone with a small diaphragm and a length of tube connected to the inlet. The tube's cross sectional area is different from the front and back volumes.



Figure 10: A moving structure with an area discontinuity. The horizontal surfaces displace an acoustic volume velocity equal to the product of U_0 and $s_2 - s_1$

incorporates the motion due to the base.

Equations (24) and (25) can be used for any microphone that has a defined transfer matrix for the back volume [B] and microphone [T]. We will use the geometry shown in Figure 9, which has area discontinuities to account for a smaller diaphragm area, s_d and the inlet channel area s_2 .

$$[T] = [L^3]([J^t][L^2]([J^f]([J^b] + [S^b]) + [S^f]) + [S^t])$$
(31)

and

$$[B] = [J^b][L^1] + [S^b], \qquad (32)$$

where the uniform sections are $[L^1]$, $[L^2]$, and $[L^3]$, the three moving discontinuities are

- $[\mathbf{J}^t]$ and $[\mathbf{S}^t]$, discontinuity between s_1 and s_2 before the tube,
- $[J^f]$ and $[S^f]$, the discontinuity between s_d and s_1 in front of the diaphragm and
- $[J^b]$ and $[S^b]$, the discontinuity between s_1 and s_d behind the diaphragm.

The transfer matrix model for P_a is found using (24), 25, and 9 shown in Figure 11 alongside the low frequency approximation:



 $P_a \approx \rho_0 \left(\frac{L_1}{2} + L_2 + L_3\right).$ (33)

Figure 11: The non-uniform (Figure 9) transfer matrix model agrees with the Taylor approximation (33) at low frequencies. The ratio between the inside area and the tube area was chosen to be $s_1/s_2 = 20$, and the length of the tube is equal to the length of the front volume ($L_2 = L_3$).

4 Finite element model

A finite element model was created to obtain, an at least partial, verification of the results from our idealized transfer matrix model. A 1 micrometer thickness silicon diaphragm, which is fixed to the microphone at its edge, is situated between two bodies of air having dimensions similar to those in the previous section. This finite element model exhibits the length-dependence predicted in the transfer matrix models.

4.1 Geometry

The model is comprised of a diaphragm, back volume, and front volume. The back and front volumes are cylinders of air, separated by the diaphragm, a circular disk (Figure 12). The computational work is reduced by using two symmetry planes as shown in Figures 13 and 14.



Figure 12: The microphone in the finite element model contains a diaphragm separating a front volume from a back volume. This diaphragm is fixed to the microphone at its edge.

The fluid structure interaction flag is set on elements which share nodes with the diaphragm. The source of acoustic excitation is a harmonic pressure condition at the inlet surface. The source of acceleration excitation is a harmonic velocity condition on the bottom surface as well as harmonic displacement of the edge of the diaphragm. The diaphragm is meshed



Figure 13: The air is meshed with FLUID220 and FLUID221 elements

with two coupled layers of SHELL281 elements so that one layer interacts with the front volume and another layer interacts with the back volume [8]. The edges of the diaphragm are constrained to the microphone: They are fixed when the microphone is stationary and they displace with the same harmonic function as the bottom when the microphone accelerates.



Figure 14: The diaphragm is meshed with two layers of SHELL281 elements.

4.2 Dependence on length

The five models listed in Table 1 were chosen so that P_a can be simulated for several values of L_1 and L_2 . In order to use (27)

 Table 1: Lengths of front and back volume for the five finite
 element models.

Model	L_1	L_2
1	$1.0\mathrm{mm}$	$0.1\mathrm{mm}$
2	$1.2\mathrm{mm}$	$0.1\mathrm{mm}$
3	$1.4\mathrm{mm}$	$0.1\mathrm{mm}$
4	$1.0\mathrm{mm}$	$0.2\mathrm{mm}$
5	$1.0\mathrm{mm}$	$0.3\mathrm{mm}$

for a microphone with diaphragm we added the diaphragm's acceleration pressure, (12)

$$P_a \approx \rho_0 (0.5L_1 + L_2) + \rho_d t_d \tag{34}$$

where $\rho_d = 2329 \,\mathrm{kg/m^3}$, the density of the diaphragm and $t_d = 1 \,\mu\mathrm{m}$ is the thickness of the diaphragm. The finite element model supports the transfer matrix formulation. When the acceleration pressure of the diaphragm is accounted for, the finite element P_a matches the transfer matrix model with various back volume (Figure 15), and front volume (Figure 15) lengths.

The microphones examined in this paper have dimensions small enough that thermoviscous effects may become significant. A model of the same microphone geometry with the full linearized Navier Stokes (FLNS) formulation was created in ANSYS. The relative difference in P_a between the adiabatic formulation and the FLNS formulations was found to be not more than 0.33% for the five models.

5 Measured results

The vibration response of several small microphones agrees with the prediction that length plays an important role in vibration sensitivity. A pair of electret microphones, Knowles models TO38-32626 and TO-24611, as well as a pair of MEMS



Figure 15: Agreement between the transfer matrix and the finite element determinations of P_a for several lengths of the back volume. The finite element model is evaluated at a harmonic frequency of 1 kHz. The acceleration pressure of the diaphragm (34) is added to the transfer matrix P_a .



Figure 16: Agreement between the transfer matrix and the finite element determinations of P_a for several lengths of the front volume. The finite element model is evaluated at a harmonic frequency of 1 kHz. The acceleration pressure of the diaphragm (34) is added to the transfer matrix P_a .

microphones, Knowles models MQM-32622 and MM15-32943 have identical design but differing effective length. Within both pairs, the microphones with longer effective lengths also had substantially greater pressure related acceleration sensitivity.

5.1 Experimental setup

All four microphones are substantially more sensitive to pressure than vibration, so their vibration sensitivity cannot be accurately obtained on a shaker without accounting for the acoustic pressure produced by that shaker. A dual input, single output spectral technique described in Walsh *et al.* [9] is used to obtain their vibration sensitivities with the equipment shown in Fig 17.

Using this technique, we solve (8) for the vibration sensitivity S_a

$$S_a(f) = \frac{U(f)}{A(f)} - S_p \frac{P(f)}{A(f)}$$

$$(35)$$

The acceleration A(f) is recorded using the laser vibrometer, and the pressure P(f) is recorded with the probe microphone. The pressure sensitivity, $S_p(f)$ is determined by subsequently using the probe microphone and the loudspeaker to obtain the microphone response to only pressure.



Figure 17: The setup used to measure microphone vibration response. A description of the equipment is given in Walsh *et al.* [9]. A microphone is subjected to pressure and vibration from a combination of the loudspeaker and the shaker. Both inputs are monitored and recorded: The pressure is recorded with a probe microphone and the vibration is recorded with a laser vibrometer.

5.2 Electret

Two of the microphones were electrets, a Knowles TO38-32626 and a Knowles TO-24611, illustrated in Figure 18. The two electrets have similar outer dimensions. They have a similar diaphragm, and similar electronic components. The key difference between the two electrets is the location of the inlet. As a result of the different inlet locations, the effective axial length of the TO38-32626 is much less than the TO-24611. We measured the outer dimensions of the electret microphones with calipers. Using these dimensions we estimated L_1 , L_2 , L_3 , and s_1/s_2 (Table 2) for a transfer matrix model of P_a . To do this, we assumed that the diaphragm bisects the length of the microphone ($L_1 = L_2$), and the thickness of the walls is negligible. We added (12) to the transfer matrix

Table 2: Approximated Electret microphone dimensions

Microphone	$L_1 (\mathrm{mm})$	$L_2 (\mathrm{mm})$	$L_3 (\text{mm})$	s_1/s_2
TO-24611	0.65	0.65	0.9	16.5
TO38-32626	1.8	1.8	1.5	6.0

model, as before in (34), based on the assumption that the diaphragm is 0.5 µm thick, and roughly the density of Mylar $(\rho = 1380 \text{ kg/m}^3)$. The transfer matrix model is compared



Figure 18: The two electret microphones contain the same components and have the same volume of air, but differ significantly in length. The TO38-32626 (left) has less length, whereas the TO-24611 (right) has more.



Figure 19: Agreement between the P_a measured from the electret microphones and the P_a determined by the transfer matrix estimates. The TO-24611 model had a larger measured P_a , than the TO38-32626 did, as predicted by their lengths.

to the measured values for P_a for the electrets in Figure 19. As predicted by the model, the longer TO-24611 measured a larger value for P_a . Both electrets measured smaller P_a values than their corresponding transfer matrix estimates. The

axial length of the two microphones may be smaller than our assumed dimensions, as we have not accounted for the size and location of e.g., the transistor, which may account for the error in modeling P_a for the electrets. A possible source of error is in the diaphragm area's orientation, which is not perpendicular to the microphone's axial direction in either microphone, but the model assumes that it is.

5.3 MEMS



Figure 20: The MEMS microphones have different effective lengths. There is no difference between these microphones except that the metal enclosure for the Knowles MQM-32622 (left) has a smaller effective length than the enclosure for the Knowles MM15-32943 (right).

Two of the microphones were MEMS microphones, a Knowles MQM-32622 and a Knowles MM15-32943, as illustrated in Figure 20. The two MEMS microphones have similar diaphragms and internal configuration, except for the metal case that encloses the back volume of the microphone. As a result, the MQM-32622 has a smaller axial length than the MM15-32943.

We measured the outer dimensions of the MEMS microphones with calipers. Using these dimensions we estimated L_1 , L_3 , and s_1/s_2 (Table 3) for a transfer matrix model of P_a . These estimates assume that the diaphragm bisects the length of the microphone ($L_1 = L_3$), and the thickness of the walls is negligible. We added (12) to the transfer ma-

Table 3: Approximated MEMS microphone dimensions

	Microphone	$L_1 \ (\mathrm{mm})$	$L_2 (\mathrm{mm})$	$L_3 (\mathrm{mm})$	s_1/s_2
Γ	MQM-32622	0.45	0	0.45	20
	MM15-32943	0.70	0	0.70	20

trix model, as before in (34), based on the assumption that the diaphragm is $0.5 \,\mu\text{m}$ thick, and made up of polysilicon $(\rho = 2330 \,\text{kg/m}^3)$.

The transfer matrix model is compared to the measured values for P_a for the MEMS in Figure 21. As predicted by the model, the longer MM15-32943 measured a larger value for P_a . The MQM-32622 and MM15-32943 both had larger P_a values than their corresponding estimates. This discrepancy may be attributed to the mass of air outside of the microphone, which is not taken into account in the transfer matrix model. It may also by attributed to the approximate nature of the dimensions and the estimated thickness of the diaphragm.

6 Conclusion

The results presented here indicate that for miniature microphones, the sensitivity to vibration is significantly affected by



Figure 21: Agreement between the P_a measured from the MEMS microphones and the P_a determined by the transfer matrix estimates. The MM15-32943 had a larger measured P_a than the MQM-32622 did, as predicted based on their lengths.

the package, or length of the air volume around the pressuresensing diaphragm. The air in this space comprises a proof mass and significantly affects the pressure related acceleration sensitivity of the microphone. At low frequencies, the air length is analogous to the thickness of the diaphragm, which is proportional to the 'acceleration pressure' that it contributes, as described by Rule *et al.*

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