Sound Attenuation Study of Micro-Scale Acoustic Package

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Certain microelectromechanical systems (MEMS), particularly MEMS gyroscopes, are notably susceptible to high power acoustic noise, especially when the noise is at or near its resonant frequency. A micro scale open-through dual expansion chamber (ODEC) array package with a continuous transmission loss (TL) in a wide frequency range is proposed to diminish the impact of such noise on the performance of MEMS gyroscopes. An analytical model based on planar wave propagation in stationary air has been developed with the consideration of the thermo-acoustic effect near the inner rigid boundary regarding small scale. Experiments with ODEC groups and control groups (non-ODEC) samples have been conducted to verify the model and compare the performances. The ODECs perform in the manner of low-pass filters and both the experimental and the analytical results exhibit greater TL in the higher frequency ranges as compared to the corresponding control samples. In addition, the resonance effects of the ODEC itself are also experimentally observed to be a key factor in influencing the TL.

NOMENCLATURE

r_t and r_c	radii of tubes and chambers
l_t and l_c	length of tubes and chambers
Δl	Length
S	cross section area of tube or chamber
p	acoustic pressure
v	volume velocity
U	particle velocity
Y	characteristic impedance
k	wave number
ω	angular frequency
c	speed of sound in air
ρ	density of air
δ_v	acoustic boundary layer thickness
μ	coefficient of dynamic viscosity
μ_e	effective coefficient of viscothermal friction

v_k	kinematic viscosity
γ	heat capacity ratio
C_p	heat capacity
C_v	specific heat
K	thermal conductivity
f	viscous force

1. INTRODUCTION

Harsh environments are a major cause of the malfunction of compact electronic devices. Micro-scale MEMS gyroscopes, utilizing extremely small proof masses, are notably susceptible to the resonance caused by incident high power acoustic noise. Dean et al. showed that MEMS gyroscopes have unreliable performance when the acoustic noise levels approach 120 to 140 dB (ref: 20 μ Pa) near the resonant frequency range of the sample devices.^{1,2} Thermal effects are also as a major cause

of deterioration in electronic devices.^{3,4} It is quite challenging to design a packaging structure achieving good acoustic attenuation, as well as good thermal characteristics for an enclosed device.⁵⁻⁷ An open-through rigid substructure is considered as one possible strategy to meet such specifications.

Considerable work has been performed in the specific area of acoustic attenuation. Yunker and Flowers offered one approach by applying micro scale Helmholtz resonator arrays to a silicon-based acoustic metamaterial, which achieved a notch filter with an attenuation of 18 dB at 14.5 kHz over a 700 Hz narrow band.⁶ Soobramaney proposed an approach of vibroacoustic isolating porous pads with an average 65% acoustic absorption at around 15 kHz over a wide band.⁷ Selamet's derivation showed that a single expansion chamber system (in large dimension) produced a transmission loss with a repeating dome-dip pattern within a frequency range from 0 to 6 kHz.⁸⁻¹⁰ Gerges et al, Munjal et al, and Kanade obtained similar conclusions to those of Selamet.¹¹⁻¹³

However, there is considerable need for attenuation over a broad frequency band, instead of periodic dome-dip attenuation patterns, to adequately protect a specific MEMS device for which the resonant frequency may be quite different to that of the nominal design frequency. In addition, the isolation package and inner structure are required to be in very small dimensions and a through-hole structure for convection is desired. With regard to the small dimensions, Munjal, Antao et al, Friend et al, and Karlsen et al provided studies of the thermoacoustic effect at rigid boundaries (or walls) causing additional transmission losses.¹⁴⁻¹⁷ Inspired by these works, this current study proposes a further extension of a micro scale open-through dual expansion chamber (ODEC) package by employing planar wave propagation in stationary air and the thermo-acoustic effect to achieve high and continuous attenuations in a wide frequency range. Corresponding experiments with several configurations of the ODECs and related control group samples (non-ODEC) were conducted to validate the theoretical predictions with respect to transmission loss (TL) already defined in abstract). The geometric effect of the TL is also investigated with respect to chamber length and radius.

2. THEORETICAL APPROACHES

The concentric configuration of a single element ODEC for plane wave propagation is illustrated in Fig. 1. It consists of three circular tubes with radius, r_t , and length, l_t , and two circular chambers with radius, r_c , and length, l_c . The areas with section lines represent the solid rigid structures, and the blank area represents the fluid medium, air.

As illustrated in Fig. 1, the incident plane wave at the entrance of the ODEC element can be described by the acoustic pressure $p_i = A_i + B_i$ and the volume velocity $v_i = \frac{1}{Y_x}(A_i - B_i) = u_i \rho_0 S$, where u_i is the particle velocity associated with p_i governed by the wave equation in Eq. (1).

$$\frac{\partial^2 p}{\partial x^2} = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2}. \quad (1)$$

The parameters ρ_0 and S represent the density of air at 20°C and the cross-section area of tube or chamber. The acoustic pressure and volume velocity of the downstream ($x > 0$) can be expressed as follows:

Figure 1a. Cross section view in 2-D and configuration of the ODC element.

Figure 1b. Magnified cross section picture of the ODC array, corresponding to (a).

$$p_x = A_i e^{-jk\tilde{l}_t} + B_i e^{+jk\tilde{l}_t} = (A_i + B_i) \cos k\tilde{l}_t - j(A_i - B_i) \sin k\tilde{l}_t = p_i \cos k\tilde{l}_t - jY_x v_i \sin k\tilde{l}_t; \quad (2)$$

$$v_x = \frac{A_i e^{-jk\tilde{l}_t} - B_i e^{+jk\tilde{l}_t}}{Y_x} = \frac{(A_i - B_i)}{Y_x \cos k\tilde{l}_t} - \frac{j(A_i + B_i)}{Y_x \sin k\tilde{l}_t} = v_i \cos k\tilde{l}_t - jp_i / Y_x \sin k\tilde{l}_t; \quad (3)$$

$$\tilde{l}_t = \Delta l + l_t. \quad (4)$$

$k = \frac{\omega}{c}$ refers to the wave number with respect to the wavelength λ . Parameter $Y_x = \frac{c}{S}$ represents the characteristic impedance of a cross section of S at the distance $x = 0$. l_t and $\Delta l = \frac{8r}{3\pi}$ refer to the tube length and the corresponding length correction shown in Eq. (4).

By applying Eq. (2) to Eq. (4), the correlation between the acoustic pressure and volume velocity via the inlet and downstream ($x > 0$) can be expressed in the following transfer matrix equation:

$$\begin{bmatrix} p_i \\ v_i \end{bmatrix} = \begin{bmatrix} \cos k\tilde{l}_t & jY_x \sin k\tilde{l}_t \\ j/Y_x \sin k\tilde{l}_t & \cos k\tilde{l}_t \end{bmatrix} \begin{bmatrix} p_x \\ v_x \end{bmatrix}. \quad (5)$$

Table 1. The air properties at constant temperature.²¹

T [°C]	ρ [kg/m ³]	v_k [×10 ⁻⁶ m ² /s]	P_r	K	c	γ
20	1.205	15.11	0.713	0.0257	343.28	1.401

By repeating Eq. (5) and employing the length of chamber l_c , it can easily get the correlation between the inlet and the outlet as follows:

$$\begin{bmatrix} p_i \\ v_i \end{bmatrix} = \prod_0^x [M] \begin{bmatrix} p_o \\ v_o \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} p_o \\ v_o \end{bmatrix}; \quad (6)$$

where $[M]$ refers to the transfer matrix in Eq. (5).

Due to the micro-scale of the ODEC structure (under the radial distance threshold: $1.25 \times \delta_v = 1.25 \times \sqrt{\frac{2\mu}{\rho_0\omega}}$, and δ_v known as the acoustic boundary layer thickness), the particle velocity u_x decreases from the maximum in the center to zero at the rigid wall by the viscous force $f = \frac{\mu S(\partial u_x)}{\partial r}$, and consequently causes additional absorption. Here $\mu = v_k \rho$ is the coefficient of dynamic viscosity of the medium. v_k and ρ represent the kinematic viscosity and ambient density of air, respectively. μ is a function of temperature but independent of frequency. The characteristic impedance Y_x can be expressed as a function correlated with μ to realize the viscous absorption in the duct system,^{19,20}

$$Y_x = \frac{p_i}{v_i} = \pm \frac{v_i}{\pi r^2} \left\{ 1 - \frac{1}{r} \left(\frac{\mu_e}{2\rho_0\omega} \right)^{\frac{1}{2}} + \frac{j}{r} \left(\frac{\mu_e}{2\rho_0\omega} \right)^{\frac{1}{2}} \right\}; \quad (7)$$

where r is the radius of each section (such as the tube radii R_t and chamber radii R_c), and the minimum r is set to 45 μm to allow Y_x to be physically meaningful. μ_e is the effective coefficient of viscothermal friction as described in Eq. (8):

$$\mu_e = \mu \left[1 + \left(\gamma^{\frac{1}{2}} - \frac{1}{\gamma^{\frac{1}{2}}} \right) \left(\frac{K}{\mu C_p} \right)^{\frac{1}{2}} \right]^2; \quad (8)$$

where $\gamma = \frac{c_p}{c_v}$ is the heat capacity ratio. The parameter K is the thermal conductivity. C_p is the heat capacity at constant pressure. C_v is the specific heat in a constant volume process. The air properties used in this analysis are listed in Table 1.

Considering the magnitude of the plane wave acoustic pressure at both open ends of the ODEC structure, and assuming there is no reflection at the outlet end, which results in $p_o = A_o$ and $p_i = 2A_i - Y_x v_i$. This magnitude can be expressed in terms of elements in the transfer matrix $[T]$:

$$A_i = \frac{p_i + Y_x v_i}{2} = \left[\left(T_{11} A_o + T_{12} \frac{A_o}{Y_o} \right) + \frac{\left(T_{21} A_o + T_{22} \frac{A_o}{Y_o} \right)}{2} \right]. \quad (9)$$

Consequently, the TL can be determined as:

$$\text{TL} = 20 \log_{10} \left| \frac{A_i}{A_o} \right| = 20 \log_{10} \left[\left(\frac{Y_o}{Y_x} \right)^{0.5} \left| \frac{1}{2} \left(T_{11} + \frac{T_{12}}{Y_o} + Y_x T_{21} + \frac{Y_x}{Y_o} T_{22} \right) \right| \right]. \quad (10)$$

Figure 2a. 3-D schematic of the metamaterial package design.

Reorganizing Eq. (10) by substituting Eqs. (6), (7) and (8) into it, the terms T_{ij} become a quintic function of sines multiplying Y_x (real for $i = j$ and imaginary for $i \neq j$). Therefore, the absolute value in Eq. (10) increases from 0 in the manner of non-linear curve with increasing frequency ω .

3. EXPERIMENTAL SAMPLES AND TESTING SETUP

All samples were designed in the form of a one-side-open box with the same inner dimensions of a 25.4 mm cube. Wall thicknesses vary from 4.5 to 5 mm with 0.5 mm increment, which is correlated with the increasing chamber length l_c . The ODEC elements array, of which the tube and chamber configurations were listed in Table 2, was fabricated through the walls of each ODEC group sample. The corresponding control samples were comprised of solid walls with the same thickness as the corresponding ODEC group sample. All the ODEC group and control samples were fabricated with the same material, as illustrated in Fig. 2.

A series of experiments were conducted in the Acoustics Laboratory at Auburn University. In order to obtain the sound level measurements, an omnidirectional microphone was firmly encased by a test sample and an isolation case. The incident sound was projected perpendicularly to the side wall of the test samples with a 105 dB SPL (ref: 20 μPa) and frequency range from 0 Hz to 8200 Hz. Fig. 2c shows a schematic diagram of the experimental setup used in the acoustic testing. Due to the minute structure of the ODEC elements, variations resulting from the sample fabrication process and test setup implementation may yield unexpected outcomes. So, a series of vibration tests were conducted as well to determine each sample's natural frequencies, which was utilized as a reference factor in analyzing the experimental results.

4. RESULTS AND DISCUSSION

The theoretical model (Eq. (10)) was used to calculate a variety of transmission loss predictions for Group 1 and 2, illustrated in Fig. 3a, which were validated by the corresponding experiments. Fig. 4a shows comparisons between the model predictions and experimental results for the ODEC samples and the control samples.

The predicted TL of Group 1 sample 1 continuously increases over the frequency range 0 Hz to 8200 Hz with some mild variations. A local maximum of 22.38 dB occurs at 2800 Hz where there is a mildly convex appearance to the

Figure 2b. Photo of fabricated testing samples.

Figure 2c. The schematic of testing equipment with customized isolation case.

curve, and a local minimum of 20.25 dB occurs at 4100 Hz where there is a mildly concave appearance. The highest TL value is 45.25 dB at 8200 Hz, which is at highest frequency considered in this analysis. Similarly, convex and concave characteristics can be observed in all the prediction results for Group 1 and 2. The corresponding local maxima, minima, and highest TL values are listed in Table 2. As observed, the predicted behavior of the micro-scale ODEC are in the form of a continuous low pass filter instead of the periodic dome-dip attenuation performance, which differs dramatically from the behavior observed for chamber systems in large scale.^{8–13}

Six groups of ODEC boxes were designed, fabricated and tested to validate and compare the analytical predictions. For comparison purposes, the three samples in each group share the same total wall thickness but differ in the radii of the expansion chambers. Table 2 summarizes the specifics of the detailed geometric configurations and the experimental results of the ODEC metamaterial groups. The lengths of the expansion chambers are reduced by 250 μm for each group, which serves to decrease the total thickness of the walls. The chamber radii are held constant between Groups 1 to 3 and between Groups 4 to 6.

Fig. 4a shows a comparison between the experimentally measured TL values for the control groups and the ODEC groups. Overall, the experimental results for all ODEC groups correlate well with their corresponding analytical predictions within the same frequency band. The experimental results for

Figure 3a. Analytical predictions. Group 1, total element length: 5 mm.

Figure 3b. Analytical predictions. Group 2, total element length: 4.5 mm.

the control group samples exhibited somewhat weaker performance than the corresponding analytical predictions. The attenuation performance of the control samples is highly dependent on the material damping characteristics, which are probably not perfectly captured by the linear model assumed in the analysis. This may explain the observed differences. In contrast to the control groups, all six groups of ODEC achieve correspondingly better attenuation performance except in the frequencies below the intersection area (E). This may be due to the level of precision in the sample fabrication, as well as modeling inaccuracies.

In addition, some of the observed differences may be due to the un-modeled dynamics of the test structure. Further experiments were conducted to further evaluate these effects and are discussed in Section 4.3.

4.1. Comparison of Control Groups to ODEC Metamaterial Groups

In order to facilitate discussion of the experimentally observed behavior in Fig. 4a, several key sections of the respec-

Table 2. Detailed geometry configuration and testing results of these ODEC groups.

	Sample No.	$r_t[\mu\text{m}]$	$r_c[\mu\text{m}]$	$l_t[\mu\text{m}]$	$l_c[\mu\text{m}]$	ξ	Approximate frequency of 1st concave section [Hz]	Approximate frequency of convex section [Hz]	Approximate frequency of 2nd concave section [Hz]	TL at 8.1 kHz [dB]
Group 1	1	72	1100	500	1750	816.94	640	5315	6451	39.60
	2		1150			892.89				44.15
	3		1200			972.22				44.51
Group 2	1	72	1100	500	1500	700.23	604	5412	6834	36.85
	2		1150			765.33				35.82
	3		1200			833.34				38.38
Group 3	1	72	1100	500	1250	583.53	570	5097	6481	30.87
	2		1150			637.78				32.09
	3		1200			694.45				33.20
Group 4	1	45	900	500	1000	800.00	570	4499	6416	28.87
	2		950			891.36				32.77
	3		1000			987.66				31.05
Group 5	1	45	900	500	750	600.00	538	4219	6100	29.52
	2		950			668.52				35.27
	3		1000			740.75				32.85
Group 6	1	45	900	500	500	400.00	508	3816	5424	31.32
	2		950			445.68				37.16
	3		1000			493.83				33.98

Figure 3c. Analytical predictions. Group 3, total element length: 4 mm. **Figure 3d.** Analytical predictions. Group 4, total element length: 3.5 mm.

tive curves are denoted by labels, as indicated in the following descriptions. “A” denotes the first concave section of the ODEC and control samples. “B” denotes the second concave section of the ODEC and control samples. “C” denotes the largest peaked convex section of the ODEC samples. “D” denotes the largest peak of the control sample. “E” denotes the intersection region between the control and ODEC curves.

Inspection of the experimental results for the control samples of Group 1 shows a low peak in the starting frequency range (A), from 0 to 0.5 kHz at around 10–12 dB. The maximum TL for the Group 1 control samples (D) occurs at 1.2 kHz with an attenuation of 37.61 dB. For frequencies above that associated with the maximum TL, the TL decreases to 21.36 dB at approximately 6.5 kHz before rising to approximately 25 dB at the end of the frequency range. Similar characteristics are observed for all five of the other control group samples, as well. After reaching the maximum attenuation level around 38 dB

at about 1 kHz, the TL generally shows a sharply decreasing trend corresponding to the decreasing of wall thickness.

The experimental ODEC results largely agree with the corresponding analytical predictions over the entire frequency band. Unlike the control samples, the ODEC sample results showed similar transmission loss characteristics to those predicted by the model. However, there are several differences between the experimental results and the analytical predictions. The first is a low peak region (similar to that observed for the control samples but of lower amplitude) which has its highest TL at about 8 dB at the center frequency range of 0.5 to 0.6 kHz and an adjacent concave section (A) with a minimum TL around 0.7 kHz. There is a second concave section (B) which show a minimum attenuation at the center frequency range of 5.4 to 6.8 kHz (B). Between the two concave regions, there is a peaked convex section (C), which also shows variation between the model prediction and the exper-

Figure 3e. Analytical predictions. Group 5, total element length: 3 mm.

Figure 3f. Analytical predictions. Group 6, total element length: 2.5 mm.

imentally observed results. The measured TL values for frequencies above the concave sections of the curves converged to the corresponding analytical results. All the metamaterial TL values are higher than those of the corresponding control groups after the frequencies for which the curves cross (E), for Group 1 to 6, the values are 4.31 kHz, 3.62 kHz, 2.71 kHz, 2.42 kHz, 2.28 kHz, and 2.03 kHz, respectively. The intersection frequencies decrease with the decreasing wall thicknesses of the control boxes. Table 2 and Fig. 4a summarize the results of these experiments. These results show that ODEC boxes have significantly higher transmission losses in these higher frequency ranges than do the corresponding control boxes. The TL differences between the ODEC and control boxes range from about 10 to 20 dB, with Group 1 showing the best transmission loss performance.

4.2. Effect of Geometric Configuration

Another important design consideration is the overall effect of wall thickness on transmission loss. Accordingly, the six sample groups were designed with wall thicknesses starting at

Figure 4a. Transmission loss from 0 to 8.2 kHz, Group 1.

Figure 4b. Transmission loss from 0 to 8.2 kHz, Group 2.

5 mm for Group 1, with a reduction of 0.5 mm in each group down to a wall thickness of to 2.5 mm for Group 6. For the control groups, it can be observed from inspection of Fig. 4a that the transmission loss decreases significantly with wall thicknesses except in the low-frequency range. As was described in the previous section, for the purpose of consistency, the tube length of the ODEC samples was held constant at 500 μm . The length for each of the two chambers was set at a starting length of 1.75 mm for Group 1 and was reduced by 0.25 mm for each group down to Group 6, which resulted in the sample wall thicknesses starting at 5 mm and decreasing incrementally to 2.5 mm.

The volume ratios, ϕ , for each sample group are tabulated in Table 2. It can be observed by inspection of the analytical and experimental results from Fig. 3a and 4a, respectively, that the attenuation performance correlates to the volume ratio. For Groups 1 to 3, which share the same geometric configurations except for the chamber lengths, the TLs decrease in accordance with decreasing ϕ in the frequency range from the center frequency of the second concave section of each TL curve to the upper limit of the frequency range tested. A similar observation is also true for Groups 4 to 6 as well. Therefore, it appears

Figure 4c. Transmission loss from 0 to 8.2 kHz, Group 3.

Figure 4e. Transmission loss from 0 to 8.2 kHz, Group 5.

Figure 4d. Transmission loss from 0 to 8.2 kHz, Group 4.

Figure 4f. Transmission loss from 0 to 8.2 kHz, Group 6.

that volume ratio is a key parameter with regard to transmission loss, with a higher volume ratio generally producing a better attenuation performance.

4.3. Vibration of the Metamaterial Structure

As discussed in sections 4.1 and 4.2, there are some modest but clearly observable differences between the analytical predictions and the experimental results. These consist mainly of a convex bulge in the TL curves at moderate frequencies and concave sections that precede and follow. It is expected that these effects are related to the resonant characteristics of the gross structure of the sample boxes. In order to test this supposition, a series of vibration experiments were conducted using a vibratory shaker and a non-contacting laser displacement measurement system. The corresponding frequency responses of each group are illustrated in Fig. 4a, along with the associated transmission loss behavior.

Inspection of the resulting frequency responses, noted as “Metabox TF” curves in Fig.4, shows that there are two main peaks for each group. The first peaks appear in the frequency range from 0.5 to 0.8 kHz, with relatively small amplitudes. The second peaks, with larger amplitudes, appear in the fre-

quency range from 5.3 to 6.8 kHz. As shown in Table 3, both main resonant frequencies are almost identical to the frequencies associated with the first and second concave sections in each of the ODEC groups. Therefore, it appears that the concave sections of the TL curves (representing decreases in transmission loss) are associated with the first two resonant modes of the overall structure of the sample boxes. Likewise, the convex bulging section (representing increases in transmission loss) are associated with the corresponding anti-resonance points between the two resonant peaks.

5. SUMMARY AND CONCLUSIONS

A type of novel acoustic substructure consisting of a micro-scale open-through dual-expansion chamber (ODEC) element was devised with the objective of noise attenuation. By using an analytical approach which combined the Helmholtz equation and the thermoacoustic effect, an analytical model for a single element of the acoustic substructure was developed. Six groups of the ODEC and corresponding control groups were designed and fabricated. A series of experiments were conducted under the condition of a 105 dB noise incidence source

Table 3. Natural frequencies of all ODEC groups [kHz].

Natural Frequency	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
f_1	0.77	0.58	0.61	0.48	0.55	0.54
f_2	6.56	6.78	6.53	6.66	6.27	5.34

in a swept sine wave of from 0 to 8.2 kHz. The ODEC samples from all groups correlated well, but having some noted differences, with the overall transmission loss behavior observed from the corresponding analytical models. The ODEC groups were designed to provide improved noise attenuation in the upper-frequency range, as compared to the non-ODEC control boxes, and this result was clearly demonstrated by the experimental results. The ratio of the chamber volume to the tube volume was observed to have a strong influence on attenuation performance, with higher volume ratios, ϕ , producing increased transmission loss.

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