

# A NOTE ON THE RESONANCE FREQUENCY EQUATION OF MICROPERFORATED PANEL SOUND ABSORBER

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## Résumé

Le panneau microperforé, ou MPP pour MicroPerforated Panel, peut être considéré comme un résonateur de Helmholtz multi ou N trous. C'est un absorbeur de son léger, propre et réglable, pour lequel une première modélisation a été établie par Maa en 1975. C'est un résonateur de taille submillimétrique de diamètre (0.5–1) mm, pour fournir une résistance acoustique suffisante et une faible masse acoustique qui sont nécessaires p

our l'absorption acoustique à large bande. La propriété caractéristique d'un tel résonateur est sa capacité à absorber les ondes sonores d'une fréquence particulière, dite fréquence de résonance. Dans les applications pratiques et d'ingénierie, pour les MPP préfabriqués, il est important de déterminer la fréquence de résonance aussi précisément que possible, surtout si le panneau sera utilisé comme absorbant acoustique à une certaine fréquence. Il existe un écart important entre la valeur exacte de la fréquence de résonance d'un seul absorbeur MPP qui peut être obtenue à partir du pic de la courbe d'absorption calculée par l'équation de Maa et cette valeur qui peut être calculée par l'équation de fréquence de résonance de Helmholtz à N trous classique. Une proposition d'équation modifiée et simplifiée pour le calcul de la fréquence de résonance d'un MPP unique de diamètre de trou (0,5–1) mm, dérivée de l'équation d'absorption de Maa, est introduite. La nouvelle équation proposée a donné un bon accord et peu de déviation, la déviation maximale était d'environ 5 Hz sur la plage de fréquences de 50 Hz à 1000 Hz, à partir de la valeur exacte de la fréquence de résonance.

**Mots clés :** résonateur de Helmholtz, panneau microperforé, fréquence de résonance, réactance de masse, résistance acoustique, constante de perforation.

## Abstract

Microperforated panel, MPP, can be considered as a multi or N-holes Helmholtz resonator. It is a light, clean and tunable sound absorber, for which a first modeling was established by Maa in 1975. It is a resonator in sub-millimeter size of diameter (0.5–1) mm, to provide enough acoustic resistance and low acoustic mass reactance which are necessary for wide-band sound absorber. The characteristic property of such a resonator is its ability to absorb sound waves of a particular frequency, the so-called resonant frequency. In practical and engineering applications, for prefabricated microperforated panel, it is important to determine the resonance frequency as precisely as possible, especially if the panel will be used as a sound absorber at a certain frequency. There is high deviation between the exact resonance frequency value of single MPP absorber which can be obtained from the peak of calculated absorption curve by Maa's equation and that value which can be calculated by the classical N-holes Helmholtz resonance frequency equation. A proposed modified and simplified equation for calculating the resonance frequency of single MPP sound absorber of hole diameter (0.5–1) mm, which derived from absorption equation of Maa, is introduced. The new proposed equation gave good agreement and little deviation, maximum deviation was about 5 Hz over frequency range from 50 Hz to 1000 Hz, from the exact value of resonance frequency.

**Keywords:** Helmholtz resonator, microperforated panel, resonance frequency, mass reactance, acoustic resistance, perforation constant.

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## 1 Introduction

Acoustic resonator, which is known as Helmholtz resonator, is incorporated to provide relatively large sound absorption in narrow bands at the low frequencies ranging from as low as 50 Hz to as high as 1000 Hz. It can be tuned to provide a maximum of absorption in a determined frequency called resonance frequency. It has been used as a single-hole or in multi-holes as a perforated panel to absorb sound in specific environment. The perforated panel is placed in front of a rigid

wall acts as a resonator, the air volume between the panel and the wall plays the role of spring. It is like Helmholtz resonator, where it can be tuned at resonance frequency; however, the absorption of perforated panel covers wider frequency range than that obtained by Helmholtz resonator. In the ordinary perforated panels, the perforations are in millimeters or even centimeters, while the microperforated panel MPP is in sub-millimeter size of diameter (0.5–1) mm, to provide enough acoustic resistance and low acoustic mass reactance which are necessary for wide-band sound absorber, without using additional fibrous or porous materials [1]. According to Xinmin Shen and et al, the diameter of the hole  $d$  should be smaller than 2.0 mm ( $2.0 \text{ mm} \geq d \geq 0.1 \text{ mm}$ ), the thickness  $t$

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of the panel should be larger than 0.1 mm ( $t \geq 0.1$  mm) and the distance  $b$  to the neighboring microholes should be larger than 1.0 mm ( $b \geq 1.0$  mm) [2]. Perforation of the MPP sound absorber less than 1.0% [3], while X. Hua and D. W. Herrin set the perforation ratio to 5.0% [4]. MPP has found applications in a wide variety of technologically significant problems. Tang and Siriango [5] provide an excellent discussion of the use of this resonator in reducing the organized oscillations inside jet engines, rocket combustors and furnaces. It has been proved that microperforated-panel absorber can effectively reduce noise of communication products at low frequency [6]. Microperforated panels may be fabricated from any sheet material, from cardboard, plastic or plywood to sheet metal with any finishing or decoration. Thus, they may be used in ordinary indoor conditions, or be made to withstand severe conditions, like washing, wind, temperature, steam or even flame for a short time. They are suitable for any reverberation or noise control applications [7]. Maa Dah-You [1, 7-9] studied the sound absorption coefficient of microperforated panels, which are based on the impedance of the hole. The structure and frequency characteristics of the MPP absorber are depending on the acoustic resistance  $r$ , acoustic impedance  $m$ , resonance frequency  $f_r$  and the perforation constant  $k$  [1]. Helmholtz resonator or MPP absorber are simply structures where their absorption characteristics can be exactly predictable. In practical and engineering applications, for prefabricated microperforated panel, it is important to determine the resonance frequency as precisely as possible, especially if the panel will be used as a sound absorber at a certain frequency. The classical analysis of a Helmholtz resonator predicted that its resonance frequency is independent of the shape of the cavity resonator, from which the  $N$ -holes resonance frequency equation was derived

$$f_r = \frac{c}{2\pi} \sqrt{sN/Vt^*} = \frac{c}{2\pi} \sqrt{\sigma/Dt^*}, \quad (1)$$

where  $s$  is the hole area,  $V$  is the Helmholtz resonator volume and  $N$  is the number of Helmholtz resonator holes. The resonance frequency in this equation depends entirely on three parameters; the perforation ratio  $\sigma$ , the thickness of the panel  $t$ , which is corrected to effective thickness  $t^*$ , and the distance between the panel and the wall  $D$ . The exact (true) resonance frequency value of single MPP absorber, which can be obtained from the peak of the calculated absorption curve by Maa's equation, is different from that calculated by the classical  $N$ -holes resonance frequency equation. In equation of Maa, there is an important parameter, perforation constant  $k$ , affects the value of resonance frequency beside the other three parameters. Pantou and Miller derived modified resonance frequency equation for the cylindrical Helmholtz resonator [10]; however, their equation did not give a good approximation with the true resonance frequency when applied for single MPP absorber. In this research the author proposed a modified and simplified equation for calculating the resonance frequency, which derived from absorption equation of Maa.

## 2 The Helmholtz Resonator

A Helmholtz resonator, originally created and developed by Hermann von Helmholtz in the 1850's, is a cavity with a volume  $V$  filled with a gas (usually air) connected to a hole of length (thickness)  $t$  and area  $s$  as shown in Fig. 1. Foundations of the theory of Helmholtz resonator were considered by Ingard [11]. The successful practical use of Helmholtz resonator involves exact calculation of resonance frequency and absorption coefficient for a given resonator [12].

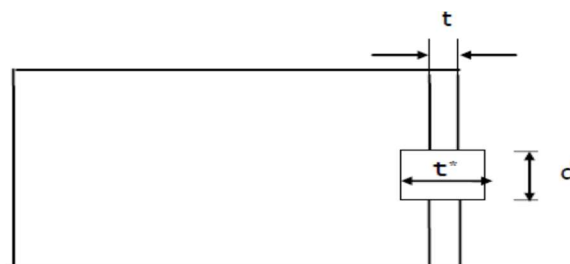


Figure 1: Single-hole Helmholtz resonator

### 2.1 Resonance Frequency of Single-Hole Helmholtz Resonator

The classical equation for calculation the resonant frequency of Helmholtz resonator is derived under the assumptions that all mass significant for oscillation of a resonator is concentrated in the hole of the resonator and that the spring constant is given by the volume of the resonator [13]. This result arises from an assumption that the dimension of resonator is small compared to the wavelength. When the dimensions of an acoustic system are often small in comparison with the wavelength of the sound, the motion of the medium in the system is analogous to that of mechanical system having lumped mechanical elements of mass, stiffness, and resistance. The air in the hole is considered to move as a unit and provides the mass element of the system. The pressure of the air within the cavity of the resonator changes as it is alternately compressed and expanded by the influx and efflux of air through the hole and thus provides the stiffness element. Since the air beyond the end of the actual constriction moves as a unit with the air in the constriction, it is necessary to add the end correction and use the effective length (thickness)  $t^*$  [11] which is greater than the actual length  $t$ . The resonance frequency at which absorption occurs is then determined by the value of the stiffness and the mass, and can be expressed as:

$$f_r = \frac{c}{2\pi} \sqrt{\frac{s}{Vt^*}}, \quad (2)$$

where  $s$  is the hole area,  $c$  velocity of sound = 340 m/s. and  $t^* = t + 4d/3\pi$ .

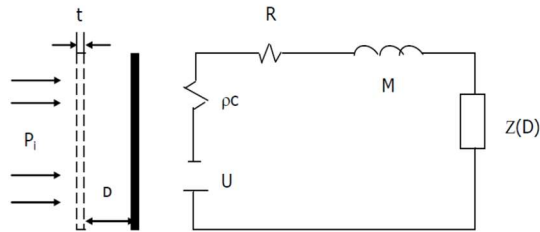
### 2.2 Resonance Frequency Of N-Holes Helmholtz Resonator

The classical resonance frequency  $f_r$  for a cylindrical resonator with  $N$ -circular holes is given by:

$$f_r = \frac{c}{2\pi} \sqrt{\frac{Ns}{Vt^*}} = \frac{c}{2\pi} \sqrt{\frac{\sigma}{Dt^*}} = \frac{c}{2\pi} \sqrt{\frac{\sigma}{D(t + \frac{4d}{3\pi})}} \quad (3)$$

### 3 The Microperforated Panel (MPP)

Microperforated panel sound absorbing construction consists of a thin panel perforated with large number of sub-millimeter holes together with an air space behind it, the structure and its equivalent circuit is shown in Fig. 2, The holes of MPP may be considered as a lattice of short



**Figure 2:** Microperforated panel sound absorber construction and its equivalent circuit.

narrow tubes separated by distances much larger than their diameters, but small compared to the wavelength of impinging sound wave. The propagation of sound waves in narrow tubes was treated early by Rayleigh [14] and Crandall [15]. They gave a simplified version for tubes with length very short compared with the wavelength. Assuming a sound pressure difference  $\Delta P$  is applied between the ends of the tube, and the ratio of  $\Delta P$  to the average value of particle velocity  $u$  over the cross-sectional area of the tube gives the specific acoustic impedance of the short tube as:

$$Z = \frac{\Delta P}{u} = j\omega\rho t \left[ 1 - \frac{2}{k\sqrt{-j}} \cdot \frac{J_1(k\sqrt{-j})}{J_0(k\sqrt{-j})} \right]^{-1} \quad (4)$$

where  $J_1$  &  $J_0$  are the Bessel functions of the first and zero order,  $k = d\sqrt{(\omega\rho/4\eta)}$  is the perforation constant,  $\eta = 1.789(10^{-5})$  kg/ms is the dynamic viscosity constant of air,  $\rho = 1.2$  kg/m<sup>3</sup> is the density of air and  $\omega = 2\pi f$  is the angular frequency. Eq. (4) is important at intermediate value of  $k$  between 1 and 10, where it is proportional to the ratio of the diameter to viscous boundary layer thickness inside the tube. For MPP, Maa introduced an approximate formula for all values of  $k$ , which is expressed as [1]:

$$Z = \frac{32\eta t}{d^2} \sqrt{1 + k^2/32} + j\omega\rho t \left( 1 + \frac{1}{\sqrt{9 + k^2/2}} \right) \quad (5)$$

The end correction of the hole thickness must be added to this equation [11].

For normal sound incidence of the sound wave on the microperforated panel, the wave motion in all the short tubes is in phase and additive, Maa [1] derived the relative (to the characteristic impedance  $\rho c$  in air) acoustic impedance of MPP with end corrections:

$$z = \frac{Z}{\rho c} = r + jx = r + j\omega m, \quad (6)$$

and

$$r = \frac{32\eta t}{\sigma\rho c d^2} k_r, k_r = \sqrt{1 + k^2/32} + \frac{\sqrt{2}}{32} k \frac{d}{t} \quad (7)$$

$$\omega m = \frac{\omega t}{\sigma c} k_m, k_m = 1 + \frac{1}{\sqrt{1 + k^2/2}} + 0.85 \frac{d}{t} \quad (8)$$

Where;  $r$  is the normalized resistance,  $m$  is the normalized mass reactance,  $k_r$  is the resistance coefficient and  $k_m$  are the mass reactance coefficient. Several authors [2, 16-18] used a resistive term 4 times greater, have given little modification to formulae 5a and 5b as.

$$r = \frac{32\eta t}{\sigma\rho c d^2} k_r, k_r = \sqrt{1 + k^2/32} + \frac{\sqrt{2}}{8} k \frac{d}{t} \quad (9)$$

$$\omega m = \frac{\omega t}{\sigma c} k_m, k_m = 1 + \frac{1}{\sqrt{9 + k^2/2}} + 0.85 \frac{d}{t} \quad (10)$$

### 4 Resonance Frequency of Single MPP Absorber

When the microperforated panel is fitted in front of a rigid wall with an air gap in-between, will make a simple resonator sound absorber. The electric equivalent circuit is shown in Fig. 2. The sound wave impinging on the panel is equivalent to source of sound pressure on the rigid wall (analogous to the open-circuit voltage in an electric circuit) and internal resistance  $\rho c$ , as that of the air. The relative acoustic resistance  $r$  and mass reactance  $m$  are given, and the relative acoustic cavity reactance is  $-\cot(\omega D/c)$ . For normal sound incidence, the sound absorption coefficient  $\alpha$  is [1]:

$$\alpha = \frac{4r}{(1+r)^2 + (\omega m - \cot \frac{\omega D}{c})^2} \quad (11)$$

For long wave,  $\cot(\omega D/c)$  can be replaced in first approximation by  $(c/\omega D)$  and accordingly  $\alpha$  can be given approximately from:

$$\alpha = \frac{4r}{(1+r)^2 + (\omega m - \frac{c}{\omega D})^2} \quad (12)$$

The maximum absorption of the single MPP sound absorber occurs when the mass reactance of the hole equals the relative acoustic reactance of the cavity. The frequency at which maximum absorption occurred is called resonance frequency, is given as

$$\omega_r m - \frac{c}{\omega_r D} = 0 \Rightarrow \omega_r^2 = \frac{c}{mD} \quad (13)$$

Considering Eq. (3), we find that the classical resonance frequency of N-holes Helmholtz resonator is easy to solve because it just depending on the perforation ratio (number of holes and their diameters), hole thickness and air gap. While in Eq. (13), the resonance frequency of MPP from Maa's acoustic impedance treatment, there is the mass reactance  $m$  which is important parameter in the computation of the resonance frequency, it includes mass reactance coefficient  $k_m$  beside the diameter and thickness of hole as it is seen in Eq. (10).  $k_m$  itself includes the perforation constant  $k$  "key parameter [1]" which is depending on the characteristic of air

(dynamic viscosity and density) inside the hole. All of these give some difficulty at solving the resonance frequency of MPP using Maa's treatments.

In order to reach our modified and simplified resonance frequency equation of microperforated panel Sound absorber, let us return to the Eq. (10) of mass reactance and rewrite it as follow:

$$m = \frac{t}{\rho c} \left( 1 + \frac{1}{\sqrt{9 + 0.5k^2}} + 0.85 \frac{d}{t} \right). \quad (14)$$

Where  $k = d\sqrt{(\omega\rho/4\eta)}$ ,  $\rho = 0.0012 \text{ g/cm}^3$  and  $\eta = 0.0001789 \text{ g/cms}$ , we can get  $k = d\sqrt{1.682\omega}$  then  $k^2 = 1.682\omega d^2$ . By replacing the value of  $k^2$  with the second term in the bracket of Eq. (14), we get:

$$m = \frac{t}{\rho c} \left( 1 + \frac{1}{\sqrt{9 + 0.841\omega d^2}} + 0.85 \frac{d}{t} \right). \quad (15)$$

The second term in bracket of Eq. (15), (i.e.  $1/\sqrt{9 + 0.841\omega d^2}$ ), is considered as the key of this research, it is depending on each of the angular frequency  $\omega$  and hole diameter  $d$ . It is inversely proportional and decreases gradually as any of  $\omega$  and  $d$  increase. Consider a hole diameter of 0.05 cm, from 50 Hz to 1000 Hz, the average value of  $(1/\sqrt{9 + 0.841\omega d^2}) \approx 0.256$ . Then by substitute in Eq. (15), the mass reactance  $m$ , is

$$m = \frac{t}{\sigma c} \left( 1 + 0.256 + 0.85 \frac{d}{t} \right) = \frac{1}{\sigma c} (1.256t + 0.85d). \quad (16)$$

Accordingly, the resonance frequency of single MPP can be given as.

For MPP of  $d = 0.05 \text{ cm}$  the resonance frequency is

$$f_r = \frac{c}{2\pi} \sqrt{\frac{\sigma}{D(1.256t + 0.85d)}}. \quad (17)$$

Similarly, for MPP of  $d = 0.06 \text{ cm}$  the resonance frequency is

$$f_r = \frac{c}{2\pi} \sqrt{\frac{\sigma}{D(1.237t + 0.85d)}}. \quad (18)$$

For MPP of  $d = 0.07 \text{ cm}$  the resonance frequency is

$$f_r = \frac{c}{2\pi} \sqrt{\frac{\sigma}{D(1.219t + 0.85d)}}. \quad (19)$$

For MPP of  $d = 0.08 \text{ cm}$  the resonance frequency is

$$f_r = \frac{c}{2\pi} \sqrt{\frac{\sigma}{D(1.204t + 0.85d)}}. \quad (20)$$

For MPP of  $d = 0.09 \text{ cm}$  the resonance frequency is

$$f_r = \frac{c}{2\pi} \sqrt{\frac{\sigma}{D(1.190t + 0.85d)}}. \quad (21)$$

For MPP of  $d = 0.10 \text{ cm}$  the resonance frequency is

$$f_r = \frac{c}{2\pi} \sqrt{\frac{\sigma}{D(1.177t + 0.85d)}}. \quad (22)$$

For all values of hole diameters from 0.05 to 0.10 cm, the value of 0.214 can be taken as an average of the term  $(1/\sqrt{9 + 0.841\omega d^2})$ , then only one equation for resonance frequency of single MPP can be introduced as:

$$f_r = \frac{c}{2\pi} \sqrt{\frac{\sigma}{D(1.214t + 0.85d)}}. \quad (23)$$

## 5 Numerical Examples and Discussion

Finally, for single MPP panel or Helmholtz resonator, the resonance frequency entirely is depending on the perforation ratio, distance air gap, thickness and hole diameter. In this section, numerical examples of the calculated results for the resonance frequency of N-holes Helmholtz resonator and single MPP absorber are given.

### 5.1 Resonance Frequency at Different Hole Diameters

First, consider a single MPP sound absorber of thickness 0.20 cm, air gap 10 cm, perforation ratio 0.5% and different hole diameters from 0.05 to 0.10 cm. By using Eq. (12), the absorption coefficient can be calculated. Fig. 3, gives the calculated absorption curves

From the calculated absorption curves, it is easy to determine the exact resonance frequency,  $f_r(\text{exact})$ , at which the maximum absorption occurs. The classical resonance frequency of  $N$ -holes Helmholtz resonator,  $f_r(\text{HR})$ , can be calculated by using the Eq. (3). The calculated resonance frequency of the same single MPP,  $f_r(\text{modified})$  can be given by using the modified Eqs. (17) to (23). The obtained values of the calculated resonance frequencies  $f_r(\text{exact})$ ,  $f_r(\text{HR})$  and  $f_r(\text{modified})$  are shown in Tab. 1.

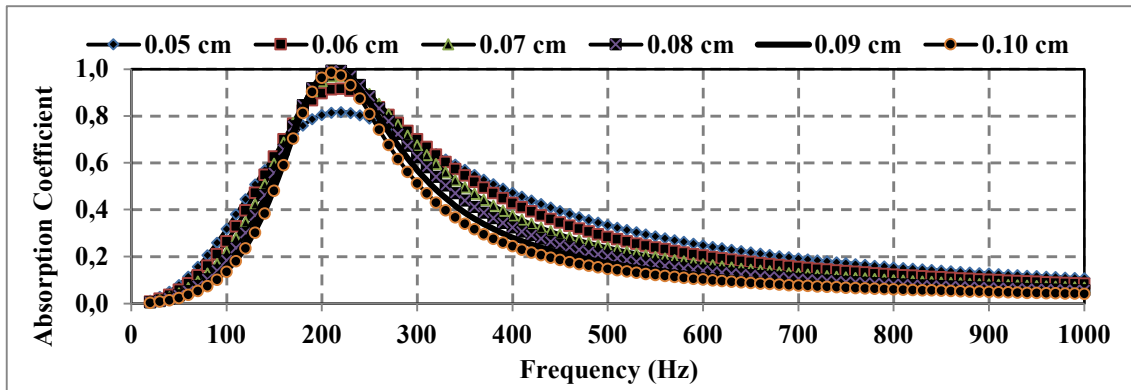
From Tab. 1; the absolute deviations of  $f_r(\text{HR})$  and  $f_r(\text{modified})$  from the exact values can be obtained. Figure 4 shows these deviations.

It is clear from Fig. 4, there are high deviations or errors between the resonance frequency values which are calculated using the classical Eq. (3) of  $N$ -holes Helmholtz resonator and that are extracted from the calculated absorption curves which give the exact values of resonance frequency of single MPP, the lowest value is 35 Hz at the largest diameter 0.10 cm. While the largest deviation is less than 5 Hz between the exact values and that are calculated by the proposed modified Eqs. (17) to (22) for all the diameters over the frequency range from 50 Hz to 1000 Hz.

In order to understand the high and small deviations between the values of  $f_r(\text{exact})$  and values of  $f_r(\text{HR})$  and  $f_r(\text{modified})$  respectively, we compared the classical Eq. (3) of  $N$ -holes Helmholtz resonator and the proposed modified Eqs. (17) to (22). The end correction in the proposed modified equation is due to the sound radiation at both ends ( $0.85d$ ) while in the classical Helmholtz resonator is due to radiation of one end ( $0.85d/2$ ). The parameter  $t$  in modified equations is multiplied by factor due to the perforation constant  $k$ , while in the

classical Helmholtz resonator there is no influence to this constant. Equation (23) which gives single resonance frequency for single MPP for all hole diameters from 0.05 to

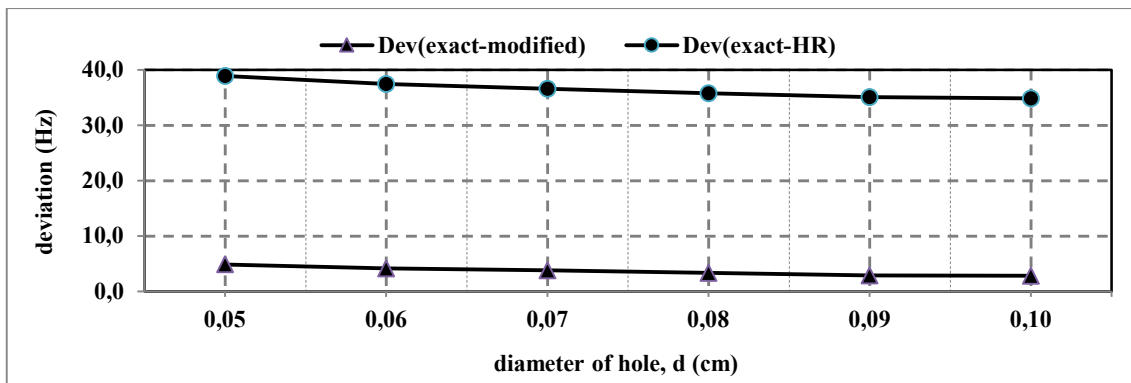
0.10 cm can be used instead of Eqs. (17) to (22). Table 2 presents the calculated  $f_r(\text{modified})$  by using Eqs. (17) to (22), and Eq. (23).



**Figure 3:** Calculated absorption coefficient of single MPP sound absorber ( $t = 0.20$  cm,  $D = 10$  cm,  $\sigma = 0.5\%$  and  $d = 0.05$  cm to 0.1 cm)

**Table 1:** Calculated  $f_r(\text{exact})$ ,  $f_r(\text{HR})$  and  $f_r(\text{modified})$  of single MPP sound absorber ( $t = 0.2$  cm,  $D = 10$  cm,  $\sigma = 0.5\%$  and  $d = 0.05$  cm to 0.1 cm)

Hole diameter cm	0.05	0.06	0.07	0.08	0.09	0.10
$f_r(\text{exact})$ Hz	218.50	217.50	216.00	214.50	213.00	211.00
$f_r(\text{HR})$ Hz	257.38	254.95	252.58	250.28	248.04	245.86
$f_r(\text{modified})$ Hz	223.40	221.63	219.79	217.86	215.88	213.84



**Figure 4:** Absolute deviation of  $f_r(\text{HR})$  and  $f_r(\text{modified})$  from  $f_r(\text{exact})$  of single MPP sound absorber ( $t = 0.2$  cm,  $D = 10$  cm,  $\sigma = 0.5\%$  and  $d = 0.05$  cm to 0.1 cm)

**Table 2:** Calculated  $f_r(\text{modified})$  by using Eqs. (17) to (23) and Eq. (23) of single MPP sound absorber ( $t = 0.2$  cm,  $D = 10$  cm,  $\sigma = 0.5\%$  and  $d = 0.05$  cm to 0.10 cm)

Hole diameter cm	0.05	0.06	0.07	0.08	0.09	0.10
$f_r(\text{modified})$ Hz, Eqs. (13a to 13f)	223.40	221.63	219.79	217.86	215.88	213.84
$f_r(\text{modified})$ Hz, by Eq. (14)	226.66	223.35	220.19	217.16	214.25	211.45
Absolute deviation Hz	3.26	1.72	0.41	0.70	1.63	2.39

**Table 3:** Calculated  $f_r(\text{exact})$ ,  $f_r(\text{HR})$  and  $f_r(\text{modified})$  of single MPP sound absorber ( $t = 0.2$  cm,  $\sigma = 0.50\%$ ,  $d = 0.05$  cm and  $D = 5$  cm to 10 cm)

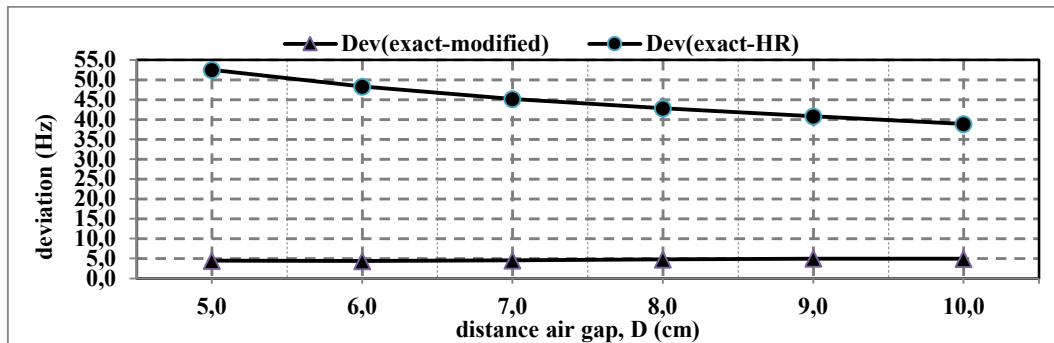
Air gap distance cm	5.0	6.0	7.0	8.0	9.0	10.0
$f_r(\text{exact})$ Hz	311.50	284.00	262.50	245.00	230.50	218.50
$f_r(\text{HR})$ Hz	364.00	332.28	307.63	287.76	271.31	257.38
$f_r(\text{modified})$ Hz	315.94	288.41	267.01	249.77	235.48	223.40

**Table 4:** Calculated  $f_r(\text{exact})$ ,  $f_r(\text{HR})$  and  $f_r(\text{modified})$  of single MPP sound absorber ( $t = 0.2$  cm,  $D = 10$  cm,  $d = 0.05$  cm and  $\sigma = 0.5\%$  to  $1.0\%$ )

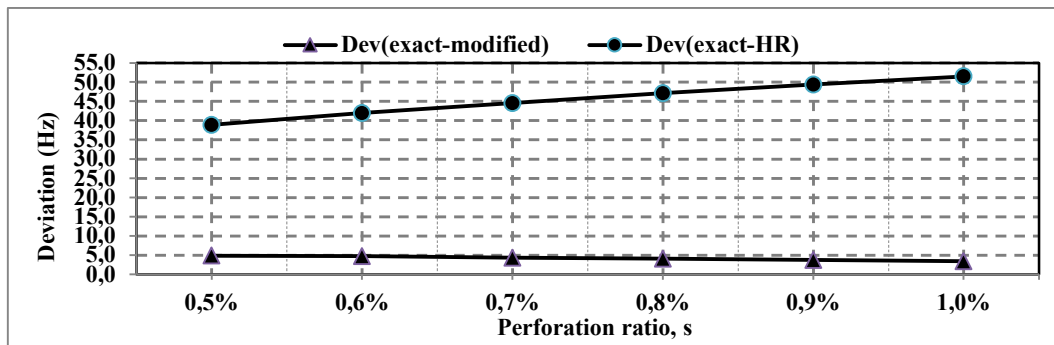
Perforation ratio	0.50%	0.60%	0.70%	0.80%	0.90%	1.0%
$f_r(\text{exact})$ Hz	218.50	240.00	260.00	278.50	296.00	312.50
$f_r(\text{HR})$ Hz	257.38	281.95	304.54	325.57	345.32	364.00
$f_r(\text{modified})$ Hz	223.40	244.72	264.33	282.58	299.72	315.94

**Table 5:** Calculated  $f_r(\text{exact})$ ,  $f_r(\text{HR})$  and  $f_r(\text{modified})$  of single MPP sound absorber ( $D = 10$  cm,  $d = 0.05$  cm,  $\sigma = 0.5\%$  and  $t = 0.1$  cm to  $0.5$  cm)

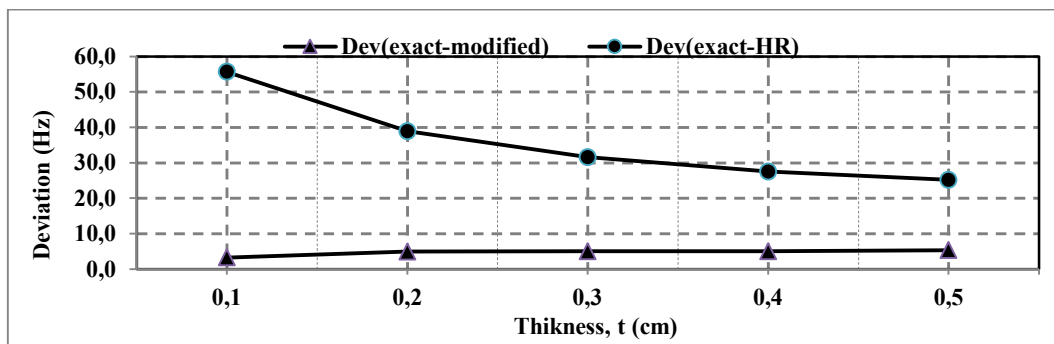
Panel thickness cm	0.10	0.20	0.30	0.40	0.50
$f_r(\text{exact})$ Hz	292.00	218.50	182.00	159.00	142.50
$f_r(\text{HR})$ Hz	347.69	257.38	213.60	186.53	167.68
$f_r(\text{modified})$ Hz	295.29	223.40	186.97	164.01	147.86



**Figure 5:** Absolute deviation of  $f_r(\text{HR})$  and  $f_r(\text{modified})$  from  $f_r(\text{exact})$  of single MPP sound absorber ( $t = 0.2$  cm,  $\sigma = 0.5\%$ ,  $d = 0.05$  cm and  $D = 5$  cm to  $10$  cm)



**Figure 6:** Absolute deviation of  $f_r(\text{HR})$  and  $f_r(\text{modified})$  from  $f_r(\text{exact})$  of single MPP sound absorber ( $t = 0.2$  cm,  $D = 10$  cm,  $d = 0.05$  cm and  $\sigma = 0.5\%$  to  $1.0\%$ )



**Figure 7:** Absolute deviation of  $f_r(\text{HR})$  and  $f_r(\text{modified})$  from  $f_r(\text{exact})$  of single MPP sound absorber ( $D = 10$  cm,  $d = 0.05$  cm,  $\sigma = 0.5\%$  and  $t = 0.1$  cm to  $0.5$  cm)

Table 2 shows little deviation of values between the calculated resonance frequencies by Eqs. (17) to (22) for each hole diameter and that calculated using Eq. (23) which is a single equation can be used for any hole diameter. So, it is acceptable to replace Eq. (23) by Eqs. (17) to (23).

## 5.2 Resonance Frequency at Different Air Gaps, Perforation Ratios and Thicknesses

To further confirmation the usefulness of the proposed equation, we performed some calculations on the single MPP at the other influencing parameters such as perforation ratio, air distance and thickness of the panel. Like the calculations which are carried out in Tab. 1. Tables 3, 4 and 5 give the exact resonance frequency from the absorption curves using Eq. (11), resonance frequency of  $N$ -holes Helmholtz resonator using Eq. (3) and the modified resonance frequency using Eq. (17). From Tabs. 3, 4 and 5; the absolute deviations of  $f_r(\text{HR})$  and  $f_r(\text{modified})$  from the exact values can be obtained. Figures 5, 6 and 7 indicate these deviations.

Like the influencing of hole diameters, Figs 5, 6 and 7 confirmed that the proposed modified equation give small deviations from the exact values extracted from the absorption curves at the other influencing parameters ( $\sigma$ ,  $D$  and  $t$ ) for the resonance frequency values, while it is still high in the case of  $f_r(\text{HR})$ . We can see that the deviation of  $f_r(\text{HR})$  decreases with increasing  $D$  and  $t$ , but it increases as  $\sigma$  increases.

## 6 Conclusions

A proposed modified and simplified equation for calculation the resonance frequency of single MPP sound absorber was introduced. This equation gives good agreement and small deviations from the exact resonance frequency values which are extracted from the calculated absorption curves by Maa's equation of single MPP absorption coefficient. It has been shown that the importance parameter to calculating the resonance frequency of single MPP is its perforation constant  $k$ . By using the pattern in this paper, it is possible for anyone to create his own equation at the desired factors and frequencies.

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