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D2.2 Absorption properties of generic plate and Helmholtz resonator structures

Author: Seppo Uosukainen

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Summary

The basic resonator functionality of the plate and Helmholtz resonator structures and structures closely related to them is based on the principle of an acoustic oscillator composed of an air spring element and an acoustic inertia element. The air spring is formed by an air volume of a container (back cavity). With the Helmholtz and microperforated plate resonators, the inertia element is formed by air mass in the pipes or holes. With the plate resonators the inertia element is formed by the plate mass. With the microperforated plate and combination resonators there also is a remarkable resistance effect due to the air viscosity affecting in the small holes or air gaps. Resistance effect also arises from absorbing materials used in the air volume. The resistance effects make the functional frequency range wider and especially with the Helmholtz and plate resonators also the maximum absorption at the resonance frequency lower.

A typical functional frequency range of a Helmholtz or plate resonator is less than one octave without absorbents and about two octaves or more around the tuning frequency with absorbent. With a Helmholtz resonator, resonance frequencies 50…1000 Hz have been typically used. With a plate resonator, a typical functional frequency range is at frequencies below 200 Hz. With a microperforated plate resonator without absorbing material, the functional frequency range can be more than two octaves, and the tuning frequencies are typically between 30…1000 Hz.

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Written by	Reviewed by	Accepted by
Seppo Uosukainen	Hannu Nykänen	Johannes Hyrynen
Senior Scientist	Principal Scientist	Deputy Technology Manager

VTT's contact address

Seppo Uosukainen, P.O. Box 1000, FI–02044 VTT, Finland

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Preface

The work described in report has been carried out at VTT Industrial Systems, in Smart Machines knowledge centre as a part of the research project "Advanced functional solutions for noise and vibration reduction of machinery" (NOVI), subproject SP2 "Sound absorption and sound insulation concepts in cabins". The total length of the project is 1.1.2011 – 31.12.2013. The project is funded by TEKES, VTT and industry.

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Seppo Uosukainen

Contents

1   Introduction

The general objective of the NOVI project is to boost the level of competence and co-operation in the field of noise and vibration control in terms of material technologies and design methods. The end results of the project will provide cutting-edge constructional and material solutions to noise and vibration challenges in the field of mechanical industry.

The key issue of the subproject SP 2 of NOVI is the development of novel sound absorption, sound insulation and hybrid materials and material structures and their performance in cabin environments. A part of the research work is focused on new modeling tools for the design of new materials and structures and predicting their performance in cabins. The main results of the subproject will be novel, thin and light weight high performance sound absorption, sound insulation and hybrid materials and structures and virtual models for the design of the use of these materials and structures in cabins.

The aim of this report of SP 2 is to introduce the plate and Helmholtz resonator structures and structures closely related to them, especially for sound absorption purposes applicable in cabins. The report is based on a literature review and contains information about the functioning and design principles and typical performances of the resonators. A typical Helmholtz or plate resonator installation inside a tractor cabin is presented in Figure 1.
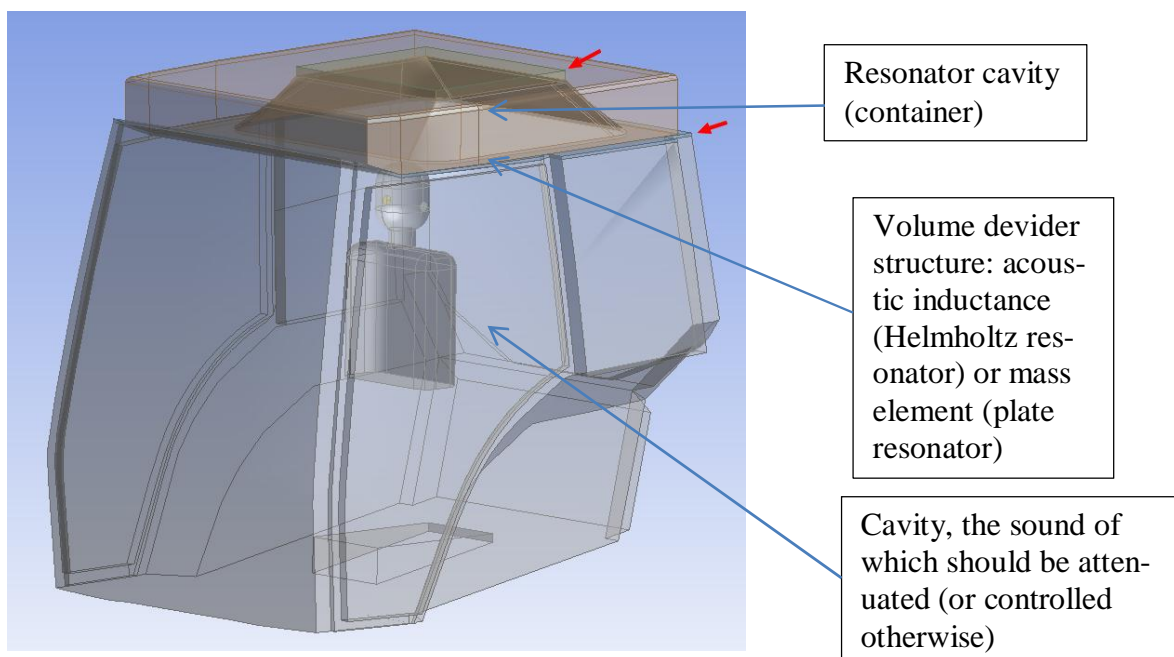

Figure 1. A typical Helmholtz or plate resonator in the roof of a tractor cabin.

2   Helmholtz resonator

2.1   Basic Helmholtz resonator

The Helmholtz resonator is an acoustic oscillator whose functioning is based on the resonance of a spring–mass system of one degree of freedom. It is formed of an acoustic capacitance (air spring) of the air volume of a container (back cavity)

and an acoustic inductance (inertia, air mass) in the connecting pipe(s), holes(s) or slit(s) in the container (and in their near vicinity). It can be used for many purposes but in this context it is handled as a sound attenuator for a larger volume (e.g., a cabin), to which the resonator is connected via the acoustic inductance. In Figure 2 are presented two principal realizations and in Figure 3 their functional measures. The right-hand side version is also called a perforated plate resonator.
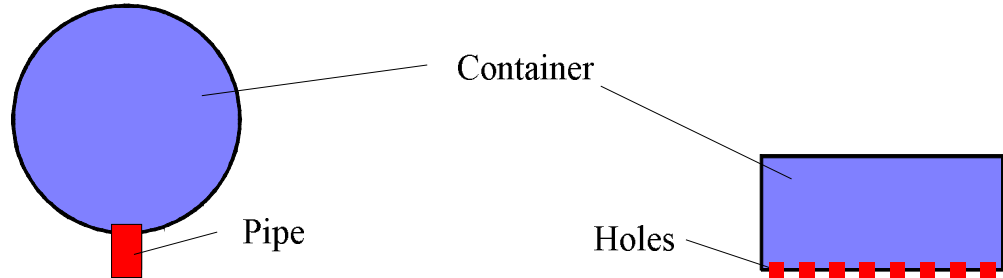

Figure 2. Helmholtz resonators. Blue part = acoustic volume element, acoustic capacitance (air spring); red parts = mass element(s), acoustic inductance formed by the moving air in the pipe and holes extending a little outside them.
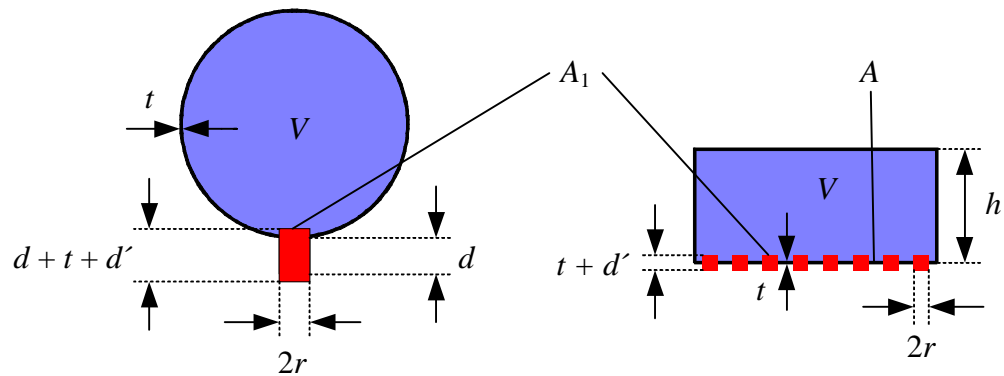

Figure 3. Functional measures of Helmholtz resonators.

The acoustic capacitance C [m³/Pa] is the ratio of volume displacement [m³] (time integral of volume velocity) and sound pressure [Pa] in an air spring element. It can be presented by the help of the compressibility Q [1/Pa] of air and the volume V [m³] of the container as

$$C = QV$$
$$Q = \frac{1}{\rho c^2}, \tag{1}$$

where ρ is the density [kg/m³] of air and c is the speed of sound [m/s] in air.

The acoustic inductance L [Pas²/m³] is the ratio of sound pressure and volume acceleration [m³/s²] (time derivative of volume velocity) in an inertia element. It can be presented for one pipe or hole by the help of the density of air, cross sectional area A_1 [m²] of the pipe or hole, the length d [m] of the pipe (measured from the outer surface of the container shell, $d = 0$ for holes) and the thickness t [m] of the container shell as

$$L_1 = \frac{\rho(d + t + d')}{A_1}, \tag{2}$$

where d' is an equivalent extra length [m] (end correction) of the pipes or holes associated to the acoustic inertia load ("attached mass") at their ends. It can be obtained from the equation below in the three different cases: (a) the output of the pipe has a rigid transversal surface around [1], (b) the output of the pipe is free; (c) holes with length $d = 0$ [2]

$$d'' = \begin{cases} 2\dfrac{8}{3\pi} r \approx 1.70\,r & \text{(a)} \\[2mm] \left(\dfrac{8}{3\pi} + \dfrac{2}{\pi}\right) r \approx 1.49\,r & \text{(b)} \\[2mm] \dfrac{\pi}{2} r \approx 1.57\,r & \text{(c)}, \end{cases} \tag{3}$$

where r is the radius [m] of the pipe or the hole. The last expression (c) also assumes that the thickness t is less than the end correction d'. Otherwise expression (a) should be used.

If there are n units of pipes or holes, the total acoustic inductance is

$$L = \frac{L_1}{n} = \frac{\rho(d + t + d')}{nA_1} = \frac{\rho(d + t + d')}{pA}, \tag{4}$$

where A is the total area [m^2] including holes or pipes and surface between them and p is its open-are ratio (total cross-sectional area of holes or pipes per total area A). Variables A and p are useful only with the perforated plate resonators, the right-hand side versions of Figure 2 and Figure 3, or similar resonators equipped with pipes, or even with resonators having a well-defined are A containing the pipes or holes (e.g., a rectangular resonator with the pipes or holes at one side).

The acoustic impedance Z [Pas/m^3] is the ratio of sound pressure and volume velocity of an acoustic system and for the Helmholtz resonator presented it is

$$Z = R + j\omega L + \frac{1}{j\omega C}, \tag{5}$$

where $\omega = 2\pi f$ is the angular frequency with frequency f and R is the acoustical resistance due to the internal losses of the resonator. The resonance frequency f_H of the resonator is the frequency at which the imaginary part of the impedance is zero when the effects of the capacitance and the inductance cancel each other

$$f_H = \frac{1}{2\pi} \frac{1}{\sqrt{LC}} = \frac{c}{2\pi} \sqrt{\frac{nA_1}{(d + t + d')V}} = \frac{c}{2\pi} \sqrt{\frac{pA}{(d + t + d')V}}. \tag{6}$$

If the air volume is rectangular having $V = Ah$, where h is the depth of the back cavity, the resonance frequency can also be presented as

$$f_H = \frac{c}{2\pi} \sqrt{\frac{p}{(d+t+d')h}} \;. \tag{7}$$

The above equations are based on an approximate one-degree-of-freedom lumped parameter presentation, and one assumption that has been done in deriving them is that all dimensions of the system are much smaller than the acoustic wavelength λ = c/f. In reality the system has distributed properties instead of lumped ones, especially at high frequencies. That is why there exist two different frequencies describing the system in reality: the resonance frequency at which the total impedance is in its minimum, and the tuning frequency at which the attenuation capability is at its maximum. Either of these equals exactly the frequency f_H above [3]. Even then, it can be used as a rough estimate for the value of the resonance frequency representing the frequency with highest attenuation of sound.

The container of the Helmholtz resonator can be equipped with separating walls, to obtain its functioning independent on the angle of incidence of the sound up to higher frequencies than without them, see Figure 4. The separating walls can also be realized in two dimensions, to form a honeycomb structure in the air volume.
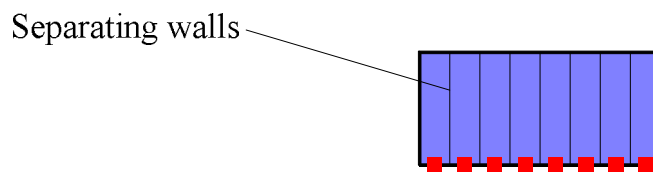

Figure 4. Helmholtz resonator with separating walls in the air volume.

The Helmholtz resonator attenuates sound typically at a very narrow frequency band around its tuning frequency. The functional frequency range can be obtained broader adding internal acoustic losses by installing absorbing material in the air volume as in Figure 5. The acoustic resistance due to the absorbent can be approximated at low frequencies by

$$R = \frac{r_0 l}{A}, \tag{8}$$

where l is the thickness [m] of the absorbing material, A its area [m^2] and r_0 is its specific flow resistance (flow resistivity) [Pas/m^2]. Also the absorbing material causes a γ-fold increase in the effective volume of that part of the air space including the absorbent, where γ = 1.4 is the adiabatic constant of air.
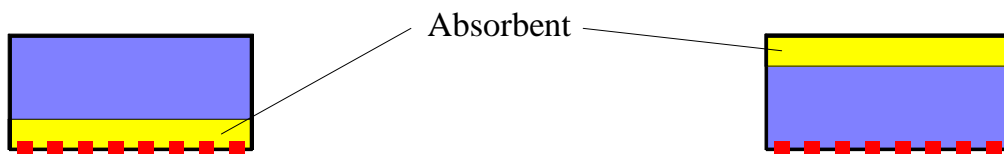

Figure 5. Helmholtz resonator with absorbent.

Adding the absorbing material leads to decrease in the maximum sound attenuation at the tuning frequency. The attenuating capability of the resonator is also affected by the placing [4] and the front surface shaping [5] of the absorbent. When the air volume is filled with absorbing material, the functioning of the resonator is independent of the incident angle of sound as with using separating walls.

A typical functional frequency range of a Helmholtz resonator is less than one octave without absorbents and about two octaves around the tuning frequency with absorbent. The resonance frequency can be tuned with a large frequency range, frequencies 50…1000 Hz have been typically used [13]. Examples of absorption characteristics of a Helmholtz resonator with one hole are presented in Figure 6. Some examples of the absorption coefficients of the perforated plate resonators as functions of frequency are presented in Figure 7. Some examples of the absorption coefficients at resonance of perforated plate resonators as functions of open-area ratio are presented in Figure 8.
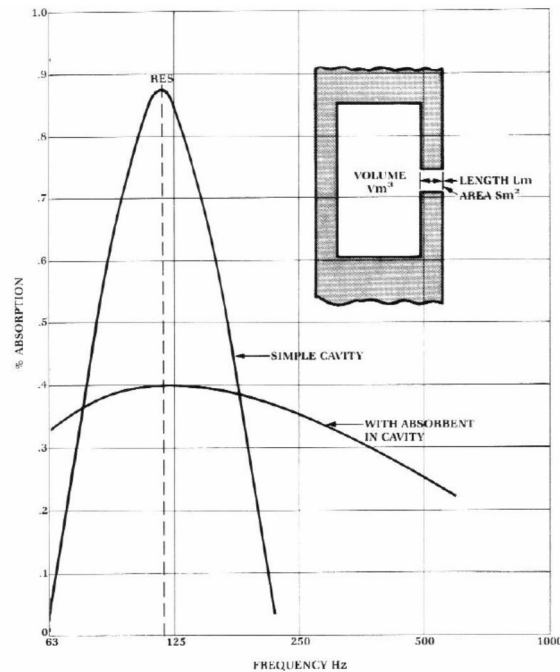

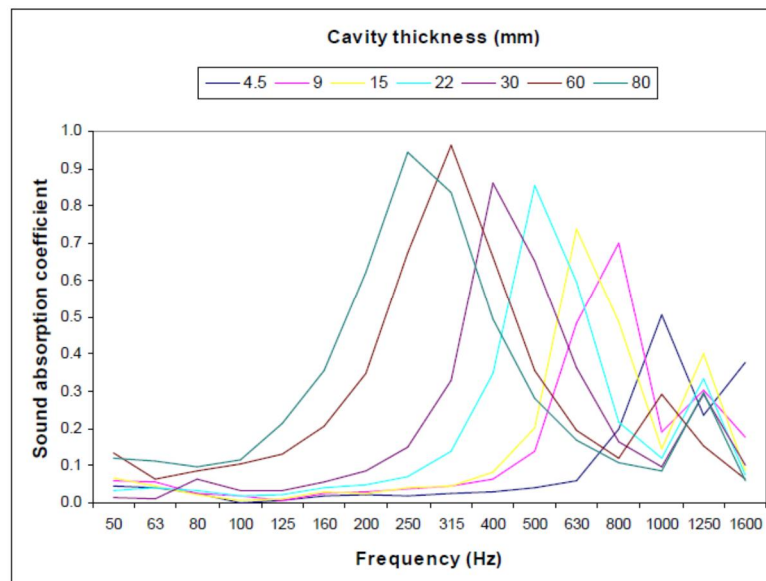*Figure 6. Typical absorption characteristics of a Helmholtz resonator [6].*

Figure 7. Sound absorption measured for different back cavity thicknesses for perforated plate resonator having 4 mm thick plywood plate with holes of radius 2 mm and 1.5 % open-area ratio, without absorbing material, measured in an impedance tube [7].
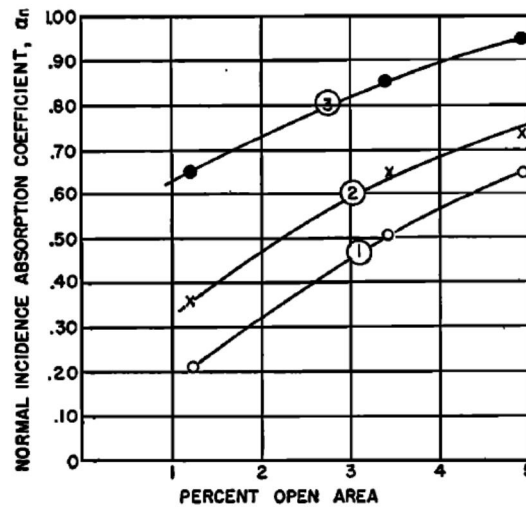
*Figure 8. Measured values of normal incidence absorption coefficient at reso-
nance as a function of open-area ratio with a perforated plate resonator with ab-
sorbent in the air volume having $r_0 l = 2.5\rho c$ (1), $r_0 l = 1.4\rho c$ (2) and $r_0 l = 0.7\rho c$ (3)
[8].*

2.2   Helmholtz resonator with a profiled Schröder diffusor

Wu *et al*. [9] has dealt with a Helmholtz resonator having an air volume formed of
a profiled Schröder diffusor, the partial air volumes with separating walls having
different depths according to Figure 9. With this kind of a solution, the functional
frequency range is got much broader especially at lower frequencies. Some exam-
ples of the absorption coefficients as functions of frequency are presented in Fig-
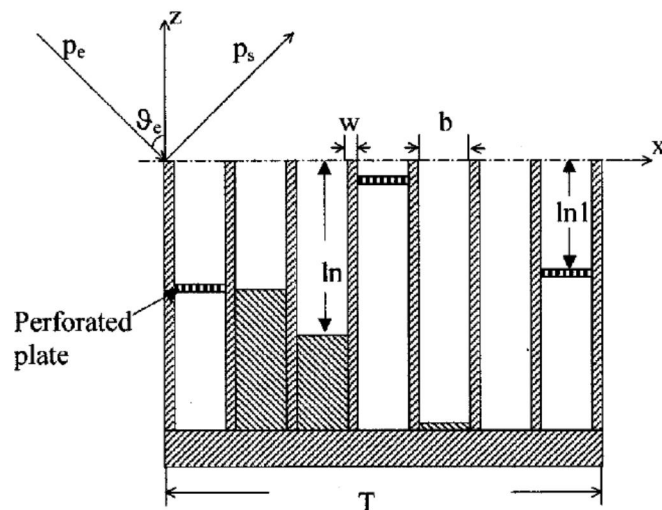ure 10.

Figure 9. One period of profiled sound absorber with perforated plates [9].
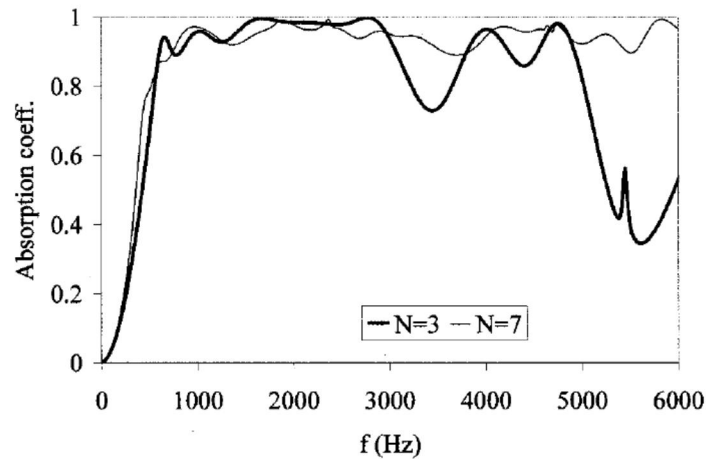
Figure 10. Absorption coefficient of some optimized profiled sound absorbers for different number of wells per period N [9].

2.3   Self-tuning Helmholtz resonator

Because the functional frequency range of a Helmholtz resonator without absorbing material is typically rather narrow, the resonator cannot be applied to a situation where the frequency content of the noise to be attenuated or the environmental circumstances change remarkably. One solution to this is a self-tuning (auto-tuning) Helmholtz resonator, the resonance frequency of which is changed with adaptive-passive means. This can be realized by changing the air volume [10, 11] or the area of the pipes or holes [12, 11] of the resonator. In Figure 11 is presented a solution to a variable volume realized by a movable wall. The variable volume can also be realized by moving the bottom end plate of the air volume. In Figure 12 is presented a solution to the variable area of the holes in duct application.
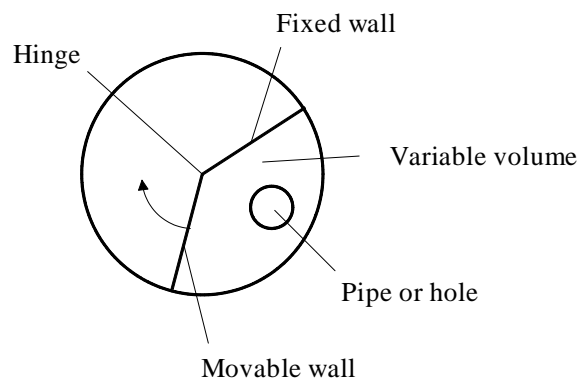

Figure 11. Cylindrical self-tuning Helmholtz resonator with a variable volume realized by a movable wall. Dimensions in the direction perpendicular to the paper surface remain unchanged. [10]
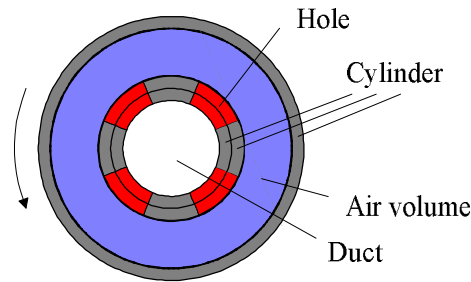
Figure 12. Cylindrical self-tuning Helmholtz resonator with a variable area of the holes in a duct. The outer cylinder is locked to the middle cylinder and the inner cylinder is fixed, which causes the change in the hole area when the outer cylinder is rotated [12]. Blue part = acoustic volume element, acoustic capacitance (air spring); red parts = mass elements, acoustic inductance formed by the moving air in the holes.

With a self-tuning Helmholtz resonator, the resonance frequency can typically be controlled within 1.5…3 octaves. The system works also with transient signals. According to Ref. [11], with the variable area of the holes a better efficiency can be achieved.

3   Plate resonator

3.1   Basic plate resonator

A plate resonator is a Helmholtz resonator type solution where the air mass of the pipes or holes has been replaced by a solid, typically thin plate structure. The functioning of the structure is based on the resonance of the spring–mass system formed by the acoustic capacitance (air spring) of the air volume and the mass of the plate. At higher frequencies, attenuation is also achieved at the eigenfrequencies of the plate. The principle of the resonator structure is presented in Figure 13.
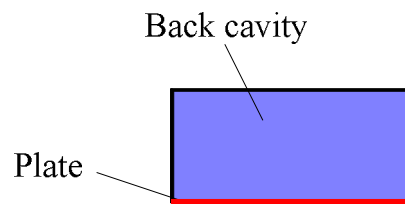
Figure 13. Plate resonator. Blue part = acoustic volume element, acoustic capacitance (air spring); red part = mass element formed by the plate.

The acoustic capacitance of the air volume is similar to that of the Helmholtz resonator and it can be obtained from Eq. (1) by the help of the volume V of the container, the air density ρ and the speed of sound c. The acoustic inductance can now be obtained from the plate mass per area m [kg/m^2] and the plate area A [m^2] as

$$L = \frac{m}{A} . \tag{9}$$

So the resonance frequency can be expressed as

$$f_P = \frac{1}{2\pi} \frac{1}{\sqrt{LC}} = \frac{c}{2\pi} \sqrt{\frac{\rho A}{mV}} = \frac{c}{2\pi} \sqrt{\frac{\rho}{mh}} \; , \qquad (10)$$

where h is the depth of the air volume and $V = Ah$.

Also this solution has a very narrow frequency range for sound attenuation that can be broadened with absorbing material inside the air volume, in which case also the maximum attenuation at the tuning frequency decreases.

The plate resonator has been mainly applied as a sound absorber in room acoustics. A typical absorption coefficient at the tuning frequency is about 0.8…1. A typical functional frequency range is at frequencies below 200 Hz, the range without absorbing material being typically about half an octave, and with absorbing material two or even more than three octaves [13]. A typical performance of a good plate resonator is presented in Figure 14.
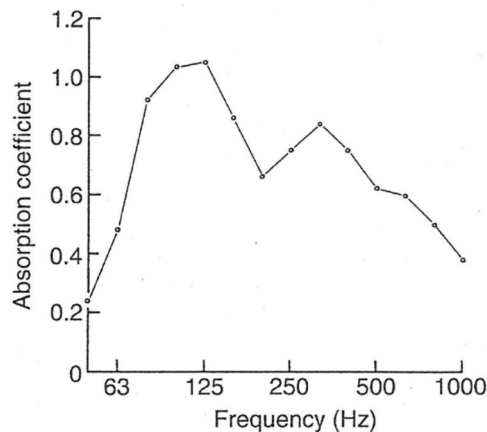

Figure 14. Typical performance of a good plate resonator [14].

3.2   Membrane resonator

The structure and the type of action of the membrane resonator are quite similar to those of the plate resonator. The difference in structure is that the plate element has been replaced by a flexible membrane, e.g., a plastic membrane. The difference in functioning is that a possible pretension makes the structure stiffer, and if the pretension is high enough the air spring in the air volume does not have any effect on the properties of the system, in which case the vibration modes and the corresponding eigenfrequencies of the membrane itself work as the plate resonator. With lower pretension the vibration modes of the membrane still affect but the acoustic capacitance of the air volume raise their eigenfrequencies. The existence of several eigenfrequencies causes a functional frequency range with many frequencies having the maximum efficiency. The separate functional frequency ranges are typically narrow. By using absorbing material in the air volume, the absorption coefficient as a function of frequency gets smoother. Increasing the pretension increases the eigenfrequencies of the membrane. [13]

4   Microperforated plate resonator

In the openings or connecting pipes of the Helmholtz resonator there also exist internal acoustic losses based mainly on the viscosity of air, giving cause for the acoustic resistance. The losses can be increased remarkably by decreasing the diameter of the holes below about 1 mm (typically 0.2...0.5 mm), in which case their transversal dimensions are of the same order than the viscous layer thickness δ_v in the frequency range under consideration [15]

$$\delta_v = \sqrt{\frac{2\mu}{\omega\rho}} \, , \tag{11}$$

where μ is the coefficient of viscosity, see Figure 15. This approach leads to so called microperforated plate resonators. Instead of the holes, also narrow slits can be used. A typical open area ratio is about 0.4...2 %. With an optimum design of the acoustic losses, the acoustic resistance of the holes is near the specific impedance of air [16, 17]. The perforated plate can be also realized with a perforated membrane or a coarse texture, e.g., a woven glass fabric [18].
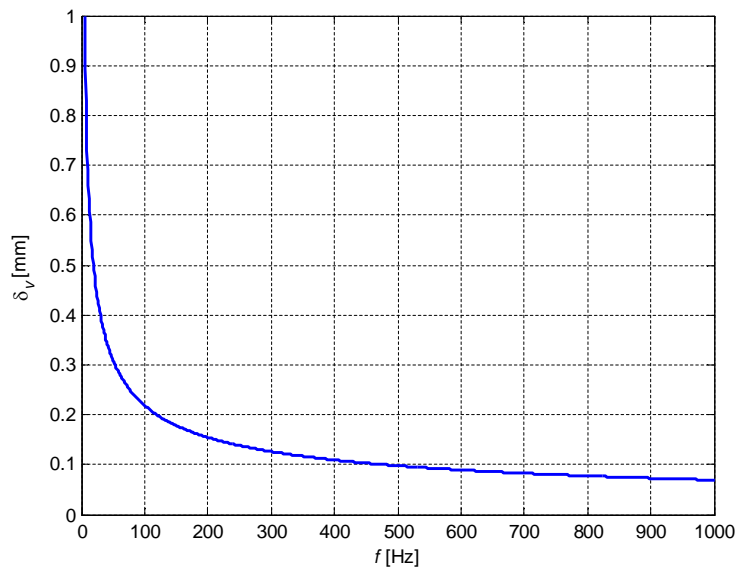

Figure 15. Viscous layer thickness near a surface in air as functions of frequency [15].

Acoustic impedance Z of the microperforated plate consists of acoustic resistance R and acoustic inductance L which are at low frequencies (radius of perforations small in wavelengths) and with low perforation ratios approximately [17, 19, 20, 21, 2, 15]

$$Z = R + j\omega L$$

$$R \approx a_1 \frac{\omega\rho}{pA}\left(t + 2r(1-p)\right)$$

$$L \approx \frac{\rho}{pA}\left(a_2 t + \frac{\pi}{2}r\right)$$

$$a_1 \approx \begin{cases} \left(\frac{2\delta_v}{r}\right)^2, & \frac{r}{\delta_v} < 4 \\ \frac{\delta_v}{r}, & \frac{r}{\delta_v} > 4 \\ 0, & \frac{r}{\delta_v} \gg 10 \end{cases} \qquad a_2 \approx \begin{cases} \frac{4}{3}, & \frac{r}{\delta_v} < 3 \\ 1 + \frac{\delta_v}{r}, & \frac{r}{\delta_v} > 3 \\ 1, & \frac{r}{\delta_v} \gg 10. \end{cases} \tag{12}$$

The first parts of R and L are due to the perforations and the second parts due to their end corrections. If the thickness t of the plate is not smaller than the end correction (3) (c) used in L, it has to be replaced by expression (3) (a).

The acoustic capacitance of the air volume is obtained from Eq. (1). The possible absorption material also has an increasing effect on the acoustic resistance R approximately by the amount of Eq. (8), and an increasing effect on the effective volume as stated below the equation. Finally, the total acoustic impedance is obtained from Eq. (5) and the resonance frequency from the zero value of the imaginary part of the impedance.

Optimal acoustic losses can be realized with microperforated plate resonator without absorbing material within a frequency range of a couple of octaves [17]. The functional frequency range (absorption coefficient at least 0.4) can be even 3…4 octaves [18]. The maximum of the absorption coefficient at the tuning frequency is of the order of 0.8…1. The tuning frequencies are typically between 30…1000 Hz [13]. An example of the absorption coefficient of a microperforated plate resonator as a function of frequency is presented in Figure 16. There can be many microperforated plates having different sizes of holes to get several resonance frequencies and wider functional frequency range, especially towards lower frequencies [17]. The functional frequency range with a resonator with two plates can be 4…5 octaves [18]. Also curved perforated plates have been used. The material of the plate does not have much effect on the functioning of the resonator [22] unless thin membrane or fabric materials are used. The holes can be done by drilling or punching (metals, glass materials), by perforating with hot needles (plastic membranes) or by weaving (glass fabrics) [23, 13].
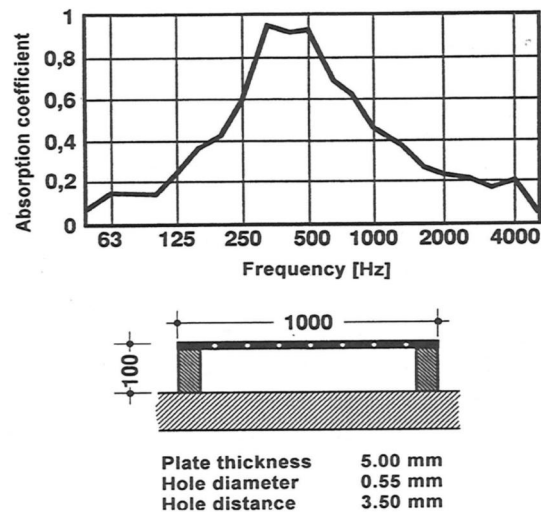
Figure 16. Absorption coefficient of a typical microperforated plate resonator, measured in a reverberation room [24].

5   Combination resonators

5.1   Double-plate Helmholtz resonator

In a double-plate Helmholtz resonator [23, 25, 26] there are two perforated plates on each other having the holes or slits not collocated. Between the plates there is a narrow air space functioning like microperforations. One of the plates can be shorter to be able to be moved to change the relative positions of the holes of the plates. The plates can also be microperforated. In Figure 17 is presented the structural principle of the resonator. The absorptive properties are about the same as with microperforated plate resonators, see examples in Figure 18. Absorption coefficient is typically between 0.6…1 at the tuning frequency (typically between 200…700 Hz).
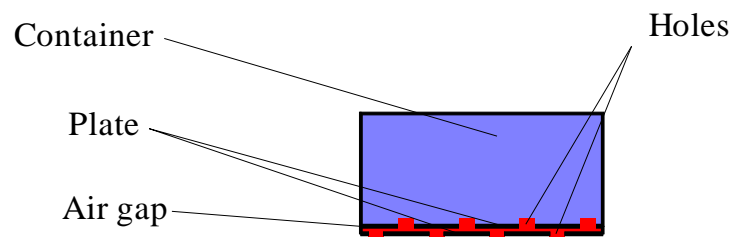

Figure 17. Double-plate Helmholtz resonator. Blue part = acoustic volume element, acoustic capacitance (air spring); red parts = mass and internal loss elements, acoustic inductance and resistance formed by the moving air in the holes extending a little outside them.
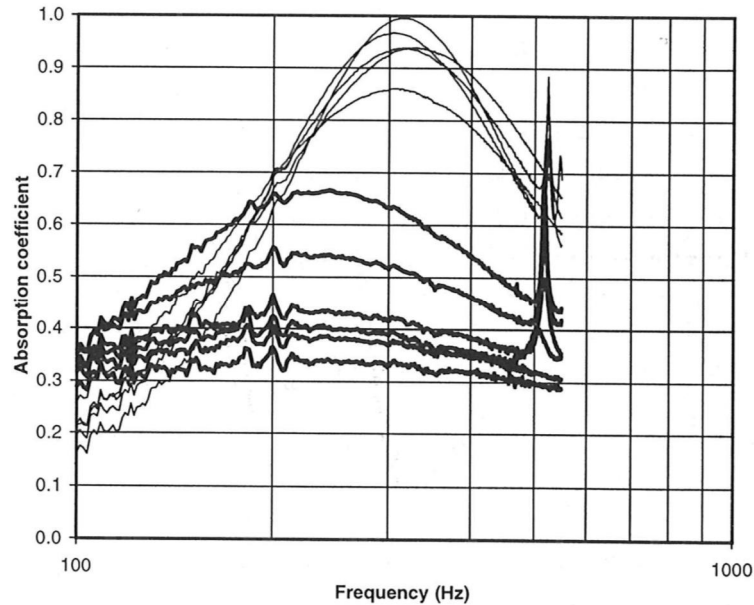
Figure 18. Measured absorption coefficients for different configurations of dou-
ble-plate Helmholtz resonators, measured in impedance tube. Thick lines: plate
separation 0.11 mm, thin lines: plate separation 0.22 mm. [25]

5.2   Perforated plate and membrane

In a similar way than with a perforated plate resonator, acoustic internal losses can
be obtained with a structure consisting of a perforated plate, under it within a dis-
tance much less than 1 mm a thin membrane, and behind that an air volume with
depth of much less than 1 mm [27]. The losses in this structure are mainly based
on viscous losses of air in the air gap between the plate and the membrane, and in
the back cavity. The losses are the higher the more the angle of incidence deviates
from normal with respect to the plate surface. The principle of the resonator struc-
ture is presented in Figure 19. Absorption coefficient is typically between 0.6…1
at the tuning frequency (typically between 300…1500 Hz). A typical measure-
ment result of the absorption coefficient of the structure as a function of frequency
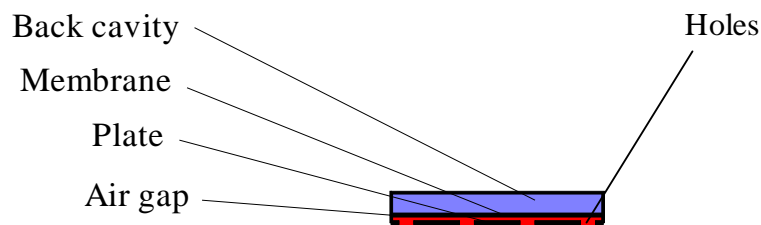is presented in Figure 20.

Figure 19. Structure formed of a perforated plate and a membrane. Blue part =
acoustic volume element, acoustic capacitance (air spring); red parts = mass and
internal loss elements, acoustic inductance and resistance formed by the moving
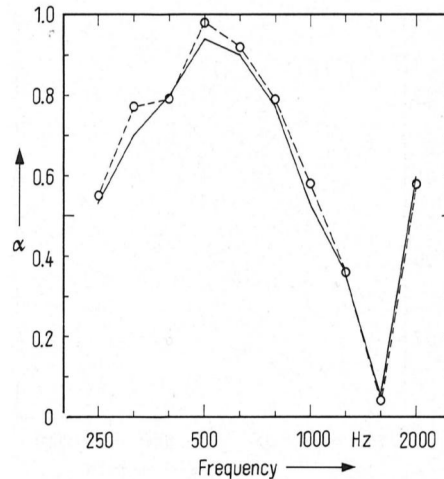*air in the holes extending a little outside them.*

Figure 20. Typical measurement result of the absorption coefficient of a perforated plate and a membrane, measured in an impedance tube. Mounting: perforated plate (---) and membrane (——) facing the incident field. [27]

6   Conclusions

The plate and Helmholtz resonator structures and structures closely related to them, especially for sound absorption purposes applicable in cabins, have been introduced. The main categories of the resonator types introduced are called Helmholtz, plate, microperforated plate and combination resonators, the last having features of the first three of them. The report contains information about the functioning and design principles and typical available performances of the resonators.

The basic resonator functionality of the structures is based on the principle of an acoustic oscillator composed of an air spring element and an acoustic inertia element. The air spring is formed by an air volume of a container (back cavity). With the Helmholtz and microperforated plate resonators, the inertia element is formed by air mass in the pipes or holes. With the plate resonators the inertia element is formed by the plate mass. With the microperforated plate and combination resonators there also is a remarkable resistance (loss) effect due to the air viscosity affecting in the small holes or air gaps. Resistance effect also arises from absorbing materials used in the air volume. The resistance effects make the functional frequency range wider and especially with the Helmholtz and plate resonators also the maximum absorption at the resonance frequency lower.

A typical functional frequency range of a Helmholtz resonator is less than one octave without absorbents and about two octaves around the tuning frequency with absorbent. The resonance frequency can be tuned with a large frequency range, frequencies 50…1000 Hz have been typically used. By using a profiled Schröder diffusor or self-tuning systems, the functional frequency range of the Helmholtz resonator can be made much wider.

With a plate resonator, a typical absorption coefficient at the tuning frequency is about 0.8…1. A typical functional frequency range is at frequencies below 200 Hz, the range without absorbing material being typically about half an octave, and with absorbing material two or even more than three octaves.

Optimal acoustic losses can be realized with microperforated plate resonator without absorbing material within a frequency range of a couple of octaves. The functional frequency range can be even 3…4 octaves. The maximum of the absorption coefficient at the tuning frequency is of the order of 0.8…1. The tuning frequencies are typically between 30…1000 Hz. The functional frequency range with a resonator with two plates can be 4…5 octaves.

7   Summary

The basic resonator functionality of the plate and Helmholtz resonator structures and structures closely related to them is based on the principle of an acoustic oscillator composed of an air spring element and an acoustic inertia element. The air spring is formed by an air volume of a container (back cavity). With the Helmholtz and microperforated plate resonators, the inertia element is formed by air mass in the pipes or holes. With the plate resonators the inertia element is formed by the plate mass. With the microperforated plate and combination resonators there also is a remarkable resistance effect due to the air viscosity affecting in the small holes or air gaps. Resistance effect also arises from absorbing materials used in the air volume. The resistance effects make the functional frequency range wider and especially with the Helmholtz and plate resonators also the maximum absorption at the resonance frequency lower.

A typical functional frequency range of a Helmholtz or plate resonator is less than one octave without absorbents and about two octaves or more around the tuning frequency with absorbent. With a Helmholtz resonator, resonance frequencies 50…1000 Hz have been typically used. With a plate resonator, a typical functional frequency range is at frequencies below 200 Hz. With a microperforated plate resonator without absorbing material, the functional frequency range can be more than two octaves, and the tuning frequencies are typically between 30…1000 Hz.

References

1. Munjal, M. L. Acoustics of Ducts and Mufflers. New York: John Wiley & Sons 1987. 328 p.
2. Morse, P. M. & Ingard, K. U. Theoretical Acoustics. New York: McGraw–Hill Book Company, 1968. 927 p.
3. Tanttari, J., Isomoisio, H., Nousiainen, E. & Veijanen, V. Helmholtz-resonaattorit äänenvaimentimina kanavasovelluksissa. Acoustic Days 11.–12.5.2011, Tampere, proceedings. The Acoustical Society of Finland. (In Finnish)
4. Brouard, B., Allard, J.-F., Bruneau, H., Lauriks, W. & Verhaegen, C. Acoustical impedance and absorption coefficients of porous layers covered by a facing perforated by parallel slits. Noise Control Eng. J. 41(1993)1, pp. 289–297.
5. Chen, W.-H., Lee, F.-C. & Chiang, D.-M. On the acoustic absorption of porous materials with different surface shapes and perforated plates. J. Sound Vib. 237(2000)2, pp. 337–355.
6. Mapp, P. The audio system designer: technical reference. England: Klark-Teknik.
7. Negro, F., Cremonini, C., Properzi, M. & Zanuttini, R. Sound absorption coefficient of perforated plywood: an experimental case study. World Conference on Timber Engineering, WCTE 2010.

8. Callaway, D. B. & Ramer, L. G. The use of perforated facings in designing low-frequency resonant absorbers. J. Acoust. Soc. Am. 24(1952)3, pp. 309–312.

9. Wu, T., Cox, T. J. & Lam, Y. W. A profiled structure with improved low frequency absorption. J. Acoust. Soc. Am. 110(2001)6, pp. 3064–3070.

10. Bedout, J. M., Franchek, M. A., Bernhard, R. J. & Mongeau, L. Adaptive-passive noise control with self-tuning Helmholtz resonators. J. Sound Vib. 202(1997)1, pp. 109–123.

11. Sato, S. & Matsuhisa, H. Semi-active noise control by a resonator with variable parameters. Inter-Noise 90, proceedings. Gothenburg: Acoustical Society of Sweden, 1990. Pp. 1305–1308.

12. Nagaya, K., Hano, Y. & Suda, A. Silencer consisting of two-stage Helmholtz resonator with auto-tuning control. J. Acoust. Soc. Am. 110(2001)1, pp. 289–295.

13. Uosukainen, S. Ilmanvaihdon uusia äänenvaimenninratkaisuja. Acoustic Days 2005, Kuopio, proceedings, pp. 60–65. Espoo: Acoustical Society of Finland. (In Finnish)

14. Fahy, F. Foundations for Engineering Acoustics. San Diego: Academic Press, 2001. 443 p.

15. Uosukainen, S., Acoustic Field Theory, Handout for lectures. Espoo: Aalto university School of Science and Technology, 2010. 613 p. (In Finnish)

16. Maa, D.-Y. Direct and accurate impedance measurement of microperforated panel. Inter-Noise 83, proceedings. Edinburgh: Institute of Acoustics, 1983. Pp. 363–366.

17. Maa. D.-Y. Microperforated-panel wideband absorbers. Noise Control Eng. J. 29(1987)3, pp. 77–84.

18. Kang, J. & Fuchs, H. V. Predicting the absorption of open weave textiles and micro-perforated membranes backed by an air space. J. Sound Vib. 220(1999)5, pp. 905–920.

19. Maa, D.-Y. Potential of microperforated panel absorber. J. Acoust. Soc. Am. 104(1998)5, pp. 2861–2866.

20. Beranek, L. L., Acoustics. New York: McGraw–Hill Book Company, 1954. 481 p.

21. Ingard, U. On the theory and design of acoustic resonators. J. Acoust. Soc. Am. 25(1953)6, pp. 1037–1061.

22. Fuchs, H. V. & Zha, X. Transparent alternative sound absorbers for the plenum of the Bundestag. Noise & Vibration Bulletin, January 1995, p. 6.

23. Fuchs, H. V. Helmholtz resonators revisited. Acustica united with Acta Acustica 86(2000), pp. 581–583.

24. Fuchs, H. V. & Zha, X. Acrylic-glass sound absorbers in the plenum of the Deutscher Bundestag. Appl. Ac. 51(1997)2, pp. 211–217.

25. Randeberg, R. T. A Helmholtz resonator with lateral elongated orifice. Acustica united with Acta Acustica 86 (2000), pp. 77–82.

26. Randeberg, R. T. Adjustable slitted panel absorber. Acta Acustica united with Acustica 88(2002), pp. 507–512.

27. Nilsson, A. C. & Rasmussen, B. Sound absorption properties of a perforated plate and membrane construction. Acustica 57(1985), pp. 139–148.