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Review on Resonator and Muffler Configuration Acoustics

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Nowadays, resonators are widely used in automobile, industrial applications, aerospace engineering, and some other fields. One of the unique characteristics of resonators which made them highly convenient is their acoustic capability to attenuate noise without having to use any acoustic absorptive material. The device acts by manipulating the sound waves to create mismatch impedance. Recent studies also suggest that the typical bulk size resonator with narrow frequency bandwidth is not the only option anymore, since there are newly designed resonators that are capable of having wide attenuation bandwidth and are smaller in size. Numerical and experimental measures were executed accordingly with the same purpose to obtain efficient noise attenuation results from varying resonators' and mufflers' configuration in terms of quantity, types, and geometry. The aim of this review is to summarize recent developments on resonator study and to try highlighting some noteworthy issues that need to be unraveled by future research. Helmholtz resonator, Quarter wave tube, Herschel-Quincke tube and helicoidal resonator are part of the numerous resonator studies that will be covered in this paper.

Keywords: resonator review; muffler; acoustics.

Abbreviations

BEM – boundary element method,
CAD – computer aided design,
dB – decibel,
dB(A) – A-weighted decibel,
DOF – degree of freedom,
EAP – electroactive polymer,
FEM – finite element method,
HQ – Herschel-Quincke,
HR – Helmholtz resonator,
HVAC – heating – ventilation and air conditioning,
Hz – hertz,
ICE – internal combustion engine,
JCA – Johnson-Champoux-Allard,
MPP – micro perforated panel,
PCD – pitch circle diameter,
PII – perforated intruding inlet,
SA – simulated annealing,
SPL – sound pressure level,
TL – transmission loss,
WHO – World Health Organization.

1. Introduction

Excessive sound coming out from machineries may not be pleasant to the ears and may have negative impact on health. This unwanted sound should be filtered in order to minimise sound pollution and adhere to international rules and regulations. A noise filter device, usually called silencer or muffler, performs silencing work through sound dissipation, reflection, or combination of both elements. The dissipative silencer consists of acoustically absorptive material lined on the silencer wall. The acoustic liner will act as a sound absorber which converts considerable amount of the sound energy coming in contact with it into heat. While the reflective silencer does not depend on any dissipative material to absorb noise, it consists of well defined geometrically tubular structure which reflects substantial part of the incident acoustic energy back to the source, hence the sound will be reduced.

Resonator is a type of reflective silencer that causes mismatch impedance to attenuate noise. Nowadays, many types of resonators are used, with Helmholtz resonator and quarter wave tube being the most popular ones. These resonators are applied to abate noise in pipes, industrial application, automotive noise, and even in home installed heating, ventilation, and air conditioning (HVAC) systems. One of the most common uses of resonator is to suppress noise from automobiles, especially in the intake and exhaust systems. In almost all vehicles, resonator is applied to reduce the duct's noise. Compared to dissipative muffler, resonators have the advantages of not depending on fibrous liner, which may be costly and insufficiently durable due to high operating temperature and exposure to unburnt carbon particles that might deteriorate its dissipative performance.

It is interesting to see how technology advancement has given impact to resonator research, development, and applications. Several review papers have discussed topics related to resonator and muffler configurations (Munjal, 1990; Tao, Seybert, 2003; Munjal, 2013; Aly, Ziada, 2016). In the present paper, we attempt to review the research that has been done on resonators and muffler configurations basing on previously published data. However, to the best of authors' knowledge, the literature on the topic is not comprehensive. The purpose of this paper is to understand how resonator types, geometry, modifications, and arrangements may effect its attenuation capabilities, and to propose area for study and improvement that needs to be explored in the future. Some of the types of resonator and muffler covered in this paper are shown in Fig. 1.

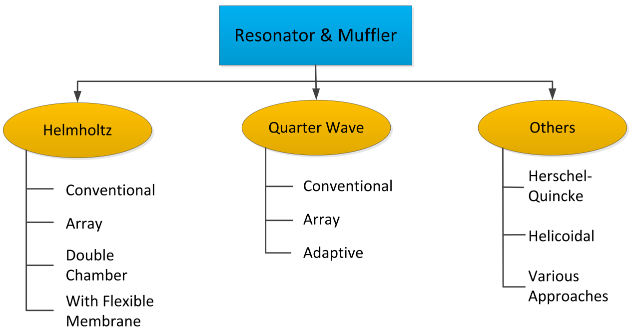


Fig. 1. Types of resonator and muffler.

2. Helmholtz resonator

Among the various types of resonators, Helmholtz resonator (HR) is the most popular type due to its sound attenuation capability and design simplicity. Helmholtz resonator is composed by a rigid wall cavity and a neck. Even though further modifications have been experimented with, i.e. Helmholtz resonator with more than one neck and using elastic membrane as its wall cavity – these are some of the research results discussed here – the base concept of a Helmholtz resonator remains as mentioned above.

When sound waves enter the Helmholtz cavity, due to friction damping, sound energy may be converted into heat energy. This sound cancelling phenomenon occurs when the sound wave frequency entering resonator's cavity is close to the resonator's natural frequency. In order to design a Helmholtz resonator of a certain resonant frequency f_r, the following formula can be applied:

$$f_r = \frac{c}{2\pi}\sqrt{\frac{A}{lV_c}}, \tag{1}$$

where V_c is the volume of resonator's cavity [m^3], l is the neck length [m], A is the cross sectional area of the neck [m], and c is the speed of sound [m/s].

There are a few parameters that can be studied further of this Helmholtz resonator concept. Shi and Mak (2015) proposed a modified Helmholtz resonator using a spiral neck. The aim is that the spiral neck will provide some extra neck length in a tight space. The curvature effect of the spiral neck was converted to an equivalent straight tube and the overall sound reduction performance of the resonator is then derived. The theoretical model showed good agreements with the finite element method (FEM) simulation and suggests that significant sound reduction can be achieved within a small space at low frequencies using the spiral neck. FEM data showed TL of more than 30 dB achieved for HR with a spiral neck of 4 turns at a low frequency, 50 Hz, compared to traditional HR with maximum extended length up to 6 mm and a resonant frequency of 105 Hz. It was also found that the implementation of the spiral neck in Helmholtz resonator not only lowers the resonant frequency of the resonator but also gives more resonance at higher frequencies. Cai *et al.*(2017) investigated the application of an extended neck or a spiral neck to take place of the traditional straight neck of a Helmholtz resonator. From their results, it was observed that a 7.54 cm and a 15.08 cm extension or spiral tube length change result in a 14 Hz and a 21 Hz decrease in the resonant frequency, respectively, thus confirming the previous findings (Shi, Mak, 2015). It was concluded that extension neck length has nearly the same effect on resonant frequency as the spiral tube length as shown in Fig. 2. The extension length could be changed flexibly to achieve the desired resonant frequency, however, it is limited to the cavity length. On the other hand, there is no limit to the number of possible turns in the spiral tube. The only limitation with the spiral tube is that each its turn length is fixed. Yang *et al.* (2014) continue the study of Helmholtz resonator performance by suggesting that manipulating the neck material of Helmholtz resonator may improve its sound absorption performance. In this work, parallel perforated ceramics with different perforation diameters were installed into the neck of a Helmholtz resonator and tested. They also put into consideration the nonlinear effects near resonant frequencies in the impedance model using revised Forchheimer coefficient. The results showed that by implementing the neck material, maximum sound absorption coefficient improved almost twice. It was shown that smaller perforation diameter of neck mate-

a)
b)

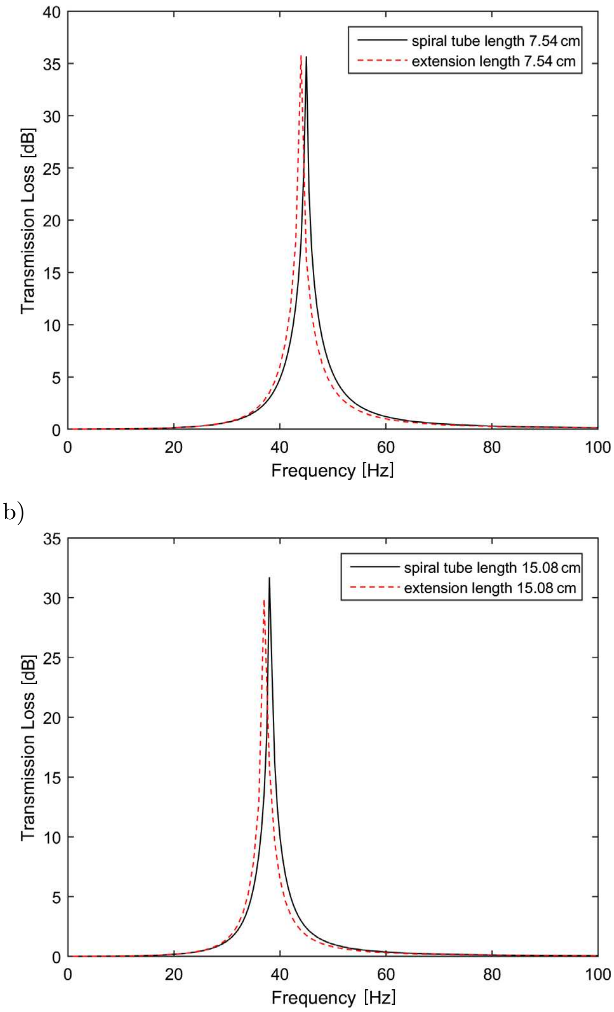


Fig. 2. Comparison of the HR with an extended neck and the HR with a spiral neck (dashed lines represent the HR with an extended neck, and solid lines represent the HR with a spiral neck) (Cai *et al.* 2017).

rial will lead to larger resistance and, therefore, a wider sound absorption bandwidth. However, a larger perforation diameter does not necessarily produce larger acoustic absorption at resonant frequencies. Comparing two neck materials of diameters 3 mm and 16 mm with the same porosity value of 0.6, showed that the former produced a wider and higher sound absorption coefficient as compared to the latter by 0.05 peak difference. It is not easy and straightforward to decide on the best perforation diameter region since they vary in porosity, neck length, resonant frequency, and the ratio between the neck sectional area and the sectional area of the acoustic duct, thus it depends on the targeted sound reduction region by users.

Wu *et al.* (2016) proposed a new type of muffler design which resembles Helmholtz resonator. From FEM simulation it can be seen that the newly designed muffler has a wider noise attenuation band compared to the quarter wavelength tube. The muffler showed similar performance to Helmholtz resonator, however, the radial size of their new muffler is significantly smaller than the regular Helmholtz muffler. The new muffler demonstrated a good noise attenuation effect in the 470–550 Hz band. The only weakness of the new silencer can be observed at 5000 rpm which was slightly louder than without the muffler due to antiresonant effect. As for the real driving experience, this kind of muffler generated noise might have little impact on it since internal combustion engine (ICE) rarely exceeds the 4000 rpm rotational speed during operation. However, the newly designed Helmholtz muffler requires further tests in real operating conditions to validate the findings. Reddi and Padmanabhan (2016) introduced a way to manipulate the resonant frequency of a Helmholtz resonator without changing its volume through intrusion. Results through boundary element method (BEM) simulation and experiments showed that the resonant frequency of the resonator increases with the growth of the number of intrusions. But this also depends on other factors such as intrusion length. As the ratio of intrusion length (l) to resonator length (L) approaches 0.5 or more, the muffler's resonant frequency will be similar to a conventional single intrusion HR. The study also showed that increasing the diameter of intrusion (pitch circle diameter (PCD)) may also increase the Helmholtz resonator's resonant frequency, as long as the ratio l/L is below 0.5.

Several studies also suggest that Helmholtz resonator installed in a duct with a high mean flow may reduce its noise elimination capability. Tang (2010) studied the drop in sound power transmission loss (TL) upon flow excitation at the Helmholtz resonator's neck from a low Mach number mean flow and he proposed several approaches to treating it. The simplified model tally with the experimental results, signifying that the increase in the grazing flow velocity at resonator's mouth leads to a higher reduction of transmission loss with test results suggested further that this effect becomes more significant once the grazing flow velocity surpasses a certain threshold. To handle this, a Helmholtz resonator named R1 was proposed which was obtained by modification of the conventional one by connecting the resonator cavity to the duct wall with a plastic tubing. The method proved to be successful since the resonator was capable of producing reasonable transmission loss even up to a flow velocity of 14 m/s, while the working frequency range of the resonator is basically kept unchanged. This happened because the modification managed to lower the static pressure differential between the resonator and the duct. The results have also showed a small increase in the low frequency spectral energy for R1, which confirms that a much weaker oscillating air jet was created from this conversion. Another design R2, formed by introducing two thin slabs at the entry inside of the resonator, leads to an increase in the neck flow resistance and the results show that good sound attenuation was maintained even up to 18 m/s. Both newly proposed HR designs clearly demonstrated good results in maintaining resonator performance with a high mean flow in duct. On the other hand, Hong *et al.* (2014) suggest the usage of inside acoustic liners to suppress the flow induced resonance. Two methods were examined for using the acoustic liners – by placing it on the side wall and at the bottom of the Helmholtz resonator. The detailed comparison of numerical and experimental data revealed that the liner on the side wall was more effective than that at the bottom in subduing resonant sound. The addition of an inside liner in the side wall as compared with the initial hard wall case reduced the measured maximum resonant sound pressure by 8.4 dB and the corresponding frequency increased a little at the mean flow velocity of 14.2 m/s as shown in Fig. 3. On the other hand, the impact of the liner at the bottom indicated that the resonance was nearly not suppressed due to the low dissipation from this kind of liner arrangement.

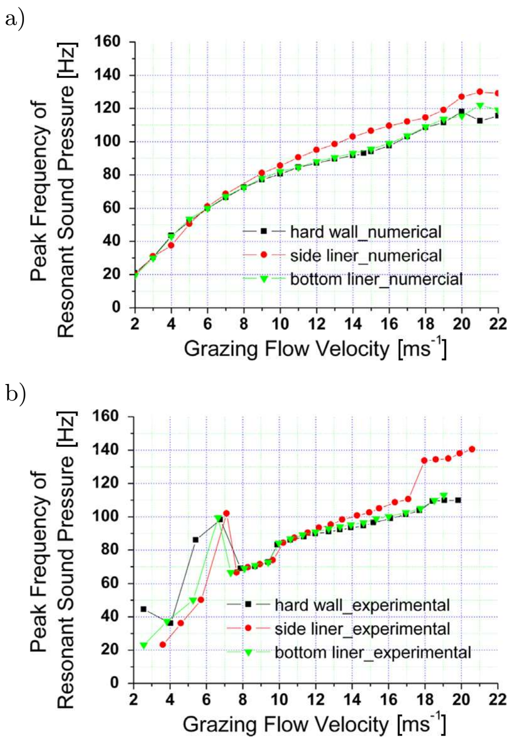


Fig. 3. Comparison of inside liner's impact on the peak frequency of resonant sound: a) predicted results and b) experimental data (Hong *et al.*, 2014).

2.1. Helmholtz resonators array

Other than modifying the design and material of a single Helmholtz resonator, a number of researchers initiated a study on the effects of resonators in array. Wang and Mak (2012) presented a theoretical model of acoustic propagation in a duct with identical side branch resonators mounted periodically. Bloch wave theory and transfer matrix method were both used to examine sound wave propagation in the distance defined periodic resonators. The results predicted by the theory showed good agreement with 3D FEM simulation and the experimental results, and may be used in the future to reduce preliminary design time and cost of Helmholtz resonators in array. In the next two years, Wang and Mak (2014) continue their study on the topic by considering the disorder in a periodic duct resonator system. The random disorder has been introduced to describe an imperfect periodic system which may appear due to defects during manufacturing. The transfer matrix method was used to study sound wave propagation in the duct and results fit well with the FEM simulation. Two cases were investigated: the disorder in periodic distance and the disorder in the geometries of Helmholtz resonators. The results showed that the periodic system is very sensitive to the defects in the periodic distance, with just two defects being able to cause obvious pattern break down of the original noise attenuation band pattern. Therefore, such defects should be avoided and taken with high precaution during manufacturing work. On the other hand, man made disorder in the geometries of Helmholtz resonators showed unexpected results. Based on the findings as shown in Fig. 4, the attenuation band will

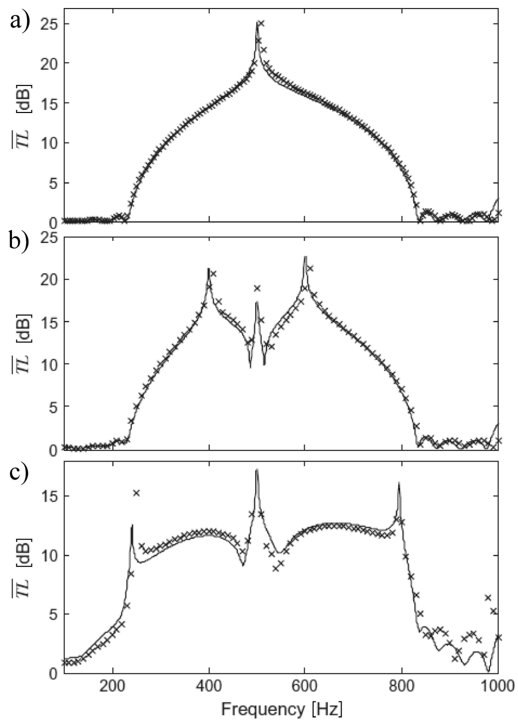


Fig. 4. Man made disorder in the geometries of Helmholtz resonators (× represents the FEM simulation and the solid lines represent the theoretical prediction): a) $f_1 = f_2 = f_3 = f_4 = f_5 = 500$ Hz, b) $f_1 = 400$ Hz, $f_2 = 600$ Hz, $f_3 = f_4 = f_5 = 500$ Hz, c) $f_1 = 250$ Hz, $f_2 = 800$ Hz, $f_3 = f_4 = f_5 = 500$ Hz (Wang, Mak, 2014).

be maintained well, provided that the variation of the resonant frequencies of the disordered Helmholtz resonators are kept within the frequency range of the main attenuation band. Yet, some new resonant peaks were also discovered. This study may be found useful in designing a system with a wide noise attenuation band but also able to abate some narrow noise peaks within it.

Cai and Mak (2016) discovered that for the same system, no matter how many Helmholtz resonators are connected or what the periodic distance is, the area under average TL curves is always the same, with only a little variation. This finding was based on theoretical analysis which then was validated with 3D FEM simulation. The results indicate that the broader the noise attenuation band achieved, the lower the peak attenuation amplitude. From these findings, they proposed a noise control zone compromising the attenuation bandwidth or peak amplitude for noise control optimisation which is bound by the highest TL amplitude for a single resonator, and the largest frequency bandwidth with the lowest TL amplitude for no. of resonator, $n = \infty$ and periodic distance, $d = \lambda_0/2$, as shown in Fig. 5. In the same year, Seo *et al.* (2016) predicted the transmission loss of a silencer system using resonator arrays at high sound pressure level (SPL). The study suggested that the resistance increases in the case of high sound pressure, due to nonlinear behavior at the resonator's neck. Therefore, the desired noise reduction performance may decrease. To study this matter, optimisation process was carried out using MATLAB software. From the results, in the linear region, the arrangement order of resonators is not important because the transmission loss at each resonator varies only to a small degree. However, in the case of a high SPL region, the arrangement order of resonators is crucial since the transmission loss at each resonator changes with the incident SPL. The optimised resonator arrangement produced an excellent performance with constant TL above 15dB at frequency range of 200 to 300 Hz for a high incident SPL. They also found out that serial arrangement has better noise attenuation than the parallel arrangement with the same number of resonators. The study also concluded that more resonators are required to maintain high noise reduction performance at a high SPL.

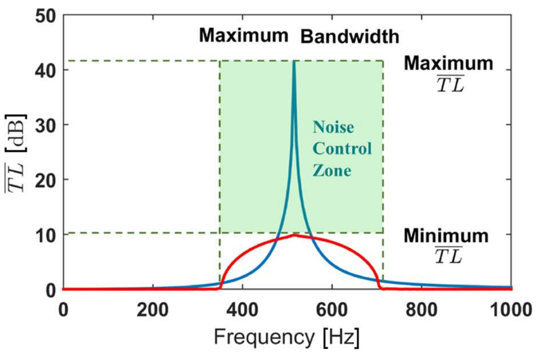


Fig. 5. Noise control zone for ducted HRs presented in the average TL curve (Cai, Mak, 2016).

Coulon *et al.* (2016) investigated the role of distance between HR in array and its sound attenuation performance in real applications. To automate the design, a 2D FEM COMSOL model has been coupled to a global MATLAB optimisation solver. This methodology was tested in two applications: a turbo compressor silencer and an air box of a two stroke engine. From the results, both applications showed TL's attenuation band improvement. The results for the redesigned air box with integrated HR array show a significant improvement with TL value almost double across 200 to 2000 Hz frequency range compared to the existing air box design. To study the influence of Helmholtz resonator quantity, two, three, and four HR arranged in an array were probed. The results showed that adding resonators helps increase the attenuation band by maintaining high TL between the peaks. However, no attenuation improvement was reported for three and four resonators. Thus adding the 4th resonator may not be necessary. Authors' also suggest connecting Helmholtz resonator to the main pipe using transversal openings instead of conventional perforated or longitudinal slots. This idea is found to be remarkable, since it gives more freedom to optimise the performance of such silencer and especially helps improve space consumption.

2.2. Double chamber Helmholtz resonator

Another unique concept in manipulating Helmholtz resonator performance is by having a single resonator with a double chamber. This application may be very useful to alter the Helmholtz resonator attenuation characteristics in a space constrained environment. Xu *et al.* (2010) studied the acoustics of a dual HR which consists of a pair of cylindrical neck and cavity connected in series perpendicular to the duct. A lumped parameter theory was established and then compared with BEM and experimental result showing reasonable agreement. The results showed that the resonant frequencies can be lowered by increasing the volume of the secondary cavity (V_2), increasing the length, or decreasing the radius of the secondary neck. At the same time, the influence of the diameter to length ratio of the secondary cavity was observed to be small. The study indicated that by decreasing V_1/V_2 ratio, first resonant frequency was able to be reduced while the total volume of the two cavities was kept the same as indicated in Fig. 6. From the results, it was also suggested that the width of transmission loss can be adjusted through changes in neck lengths with the peak frequencies remaining unchanged.

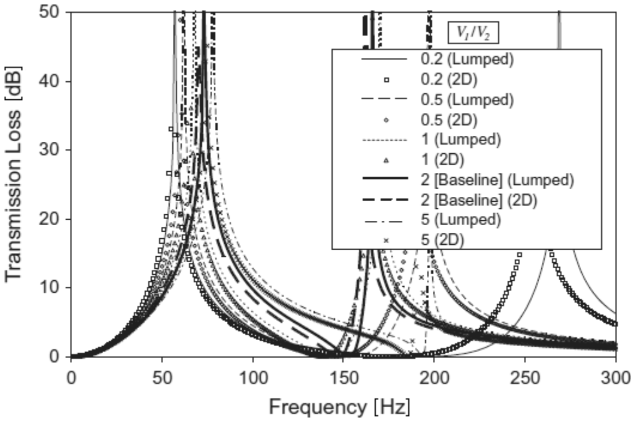


Fig. 6. Transmission loss prediction from the lumped and 2D analytical approach with varying volume ratio of the two cavities: $V_1/V_2 = 0.2$, 0.5, 1, 2, and 5 (Xu *et al.*, 2010).

Tang *et al.* (2012) continued the investigation on the effects of a double chamber HR towards its acoustic performance. The effect of having a dual chamber resonator through compartmenting was also investigated. The results indicate that the introduction of an additional chamber will produce two resonant peaks and the front cavity's resonance has a more significant impact on the sound attenuation than the rear cavity of the coupled resonator. To reach a better coupled resonator performance, it was suggested that the resonant frequency of the front chamber should be designed to be larger than that of the rear one. In most cases, the performance of the dual chamber resonator is found to be better if the resonant frequencies of the individual chambers are closer to each other. In the case of compartmenting resonator's cavity, it was shown that adding a small cavity compartment at the rear side of the resonator cavity can have a substantial effect in widening the attenuation bandwidth at 100 to 350 Hz frequency range while maintaining the sound absorption capacity of the resonator. Similar to the previous case, the results also indicated that the best improvement in the sound attenuation can be achieved by keeping the resonant frequencies of the two compartmented cavities very close to each other.

Zhao (2012) suggested a dual chamber HR in a parallel coupled Helmholtz resonator network. The concept that two resonators are connected by means of a thin compliant membrane was modelled using Green's function and experimentally tested to evaluate the resonator's performance. To absorb noise of varying frequency, the membrane vibration was dynamically tuned by applying trust region Newton conjugate gradient method. The results demonstrated that the compliant membrane motion produced additional attenuation peaks at non resonant frequencies of the resonators. However, the major peak frequencies observed were also altered and very different from the resonant frequencies of the uncoupled resonators. The author suggested that the phenomenon is due to the mechanical properties of the compliant membrane. From the parametric analysis it was found that the TL peak frequencies can be increased with the increase of membrane stiffness. According to the study, the parallel coupled resonators network was able to increase the system transmission loss up to about 25 dB over a broad frequency range. The study also suggested that the parallel coupled resonator network can give additional TL peaks in contrary to conventional resonators.

Finally, the experimental study of alternative resonator network configurations was also conducted. It involved blocking one of the resonator necks and removing the separating diaphragm (Zhao, 2012). For the first case, the results showed that the resonant frequency moved lower than the expected resonator's frequency of the non block cavity. In the second case, with the diaphragm membrane removed, the resonant frequency of the system was found to be close to the theoretical resonant frequency of the new combined resonator.

2.3. Helmholtz Resonator with a flexible membrane

One of the latest and most exciting innovations on Helmholtz resonator is the introduction of flexible membrane into the scene. Studies suggest that the sound attenuation performance of this Helmholtz resonator concept may just prove to be one of the 'game changer' for this field due to its capabilities to modify the natural response of a Helmholtz resonator. Sanada and Tanaka (2013) studied the impact of resonator with a flexible membrane installed in its cavity which allows the membrane to be excited by incident sound. Hence, the resonator acts as a two degree of freedom (DOF) system. Using the dimensionless parameter, the absorption coefficient and specific acoustic impedance of the membrane were derived analytically to determine the fundamental characteristics of the absorber, and experimental results confirmed the validity of the proposed resonator concept. From the results, it was demonstrated that in order to broaden the working frequency range of the absorber, the flexible membrane has to be lightweight, and both the internal damping and opening ratio needs to be large. The proposed resonator will have two cavities separated by a flexible panel. The back cavity does not affect the two DOF system, but it acts as a cover to avoid any sound transmitted through the absorber and released beyond the system. In the same year, Nudehi *et al.* (2013) studied the concept of Helmholtz resonator with a uniform flexible end plate. Coupling receptance models were applied to predict the receptance of the Helmholtz resonator and flexible plate assembly, which was later validated through experiments. From the model, it was predicted that the first resonant frequency of the proposed resonator would be lower than that of the unmodified Helmholtz resonator subsystem, as shown in Fig. 7. This new resonator assembly also produced multiple peak frequencies instead of a single resonant frequency and suggested that the introduction of flexible plate modified the frequency response characteristics of the resonator.

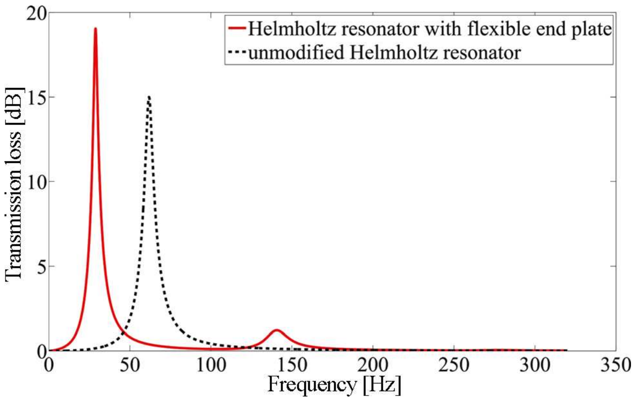


Fig. 7. Predicted transmission loss result (Nudehi *et al.*, 2013).

Kurdi *et al.* (2014) applied multiobjective optimisation formulation to design a Helmholtz resonator with a flexible end plate. A Pareto curve of alternative designs was generated in the process that quantifies the trade off between two optimisation goals: minimum resonator volume and maximum transmission loss across a specified frequency range as indicated in Fig. 8. For this study, two optimised Helmholtz resonators were selected for the study, namely design A and B, and the results then were experimentally verified. Design A provided a slightly smaller transmission loss value compared to the baseline but the resonator volume is reduced tremendously to less than a quarter of the baseline resonator. Design B produced a significant increase in the noise attenuation about 2.8 dB increment at resonant frequency and significant reduction in resonator volume as well, with the new resonator less than half the size of the baseline resonator.

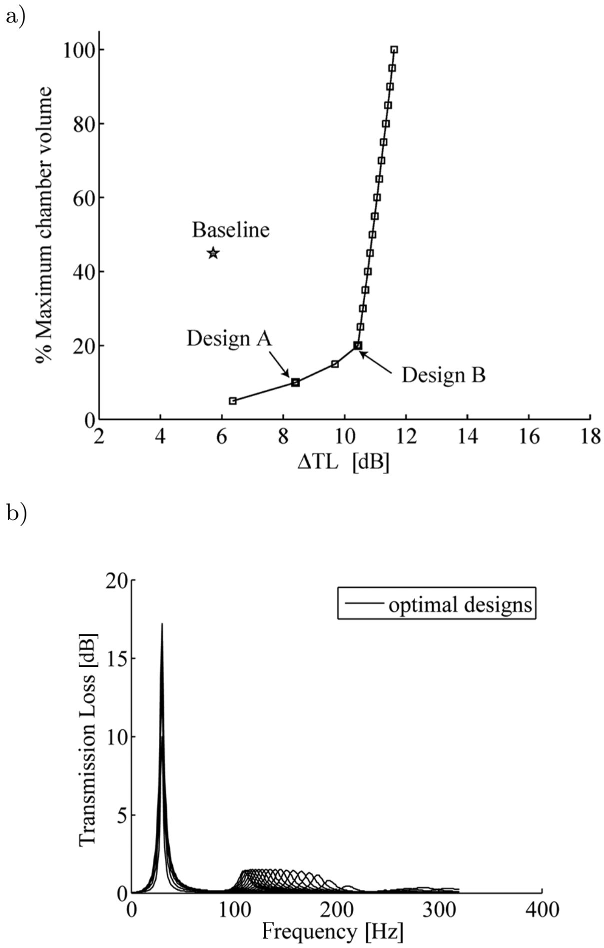


Fig. 8. Trade off curve with objective function adjusted to favour nominal desired frequency and constraint on diameter ratio (Kurdi *et al.*, 2014).

Abbad (2016) examined strategies allowing dynamic Helmholtz resonator response with the goal of providing a wider noise attenuation bandwidth. Two concepts were introduced, both based on the application of electroactive polymer (EAP) membranes. These EAP materials are unique because they exhibit a change of shape when being stimulated by an electric field. The first concept consists of replacing the resonator's rigid back plate with an EAP material membrane, while for the second one, the EAP membrane is located in the resonator's front plate. Cosmol mutliphysics software with Acoustic and Solid Mechanics packages was used to develop the numerical model. In order to model the melamine foam behaviour and viscous loss in the neck, the Johnson-Champoux-Allard (JCA) model, based on five intrinsic properties of material, namely: the flow resistivity, porosity, tortousity, viscous characteristic length, and thermal characteristic length, was applied. From the simulation results, the modified resonator with back wall cavity made from EAP material, showed a shift of the resonant frequency to a higher frequency and an antiresonant frequency appeared at 100 Hz. This most likely occurred due to the resonance from the membrane. In the case where front wall cavity is made from EAP material, two main resonances are observed. One is at a low frequency, 100 Hz, and another one is at a slightly higher frequency, 446 Hz, with large amplitude. These new induced resonant frequencies, appearing as a result of the coupling between the membrane and resonator's cavity, indicated a good sign with front wall EAP resonator assembly and showed a better potential. Yet the experimental validation of this work is needed and can be extended for future study. Summarized comparison of Helmholtz resonator variations discussed in this chapter is shown in Table 1.

Table 1. Variation of Helmholtz resonator and its characteristics.

Muffler's type	Characteristic
Helmholtz resonator with spiral neck	• Lower resonant frequencies and give more resonance at higher frequencies (Cai *et al.*, 2017; Shi, Mak, 2015) • Similar to HR with extended neck but with higher freedom of neck extension (Cai *et al.*, 2017)
Helmholtz resonator with extended neck	• Lower resonant frequencies and give more resonance at higher frequencies (Cai *et al.*, 2017)
Helmholtz resonator with porous neck material	• Sound absorption coefficient improved almost twice (Yang *et al.*, 2014)
Helmholtz resonator with added intrusions	• Resonant frequency increases with number of intrusions (Reddi, Padmanabhan, 2016)
Helmholtz resonator adaptations	• Maintain good sound attenuation at high mean flow (Cai, Mak, 2016; Coulon *et al.*, 2016)
Helmholtz resonators in array	• Adding resonators in array help to improve sound attenuation band (Cai, Mak, 2016; Coulon *et al.*, 2016) • Serial resonators' arrangement has better noise attenuation performance than parallel arrangement (Seo *et al.*, 2016) • Disorder in resonators' geometry can produce unique TL curve with new resonant peaks (Wang, Mak, 2014)
Double chamber Helmholtz resonator	• Widen attenuation bandwith (Tang *et al.*, 2012) • Two resonant peaks produced with front's cavity resonance being more significant (Tang *et al.*, 2012; Xu *et al.*, 2010) • Decreasing V_1/V_2, reduced first resonant frequency (Xu *et al.*, 2010)
Parallel coupled resonators separated by thin compliant membrane	• Additional attenuation peaks produced at non resonant frequencies (Zhao, 2012)
Helmholtz resonator with flexible membrane	• Lower first resonant frequency (Kurdi *et al.*, 2014; Nudehi *et al.*, 2013) • Able to produce higher transmission loss peak compared to conventional one (Kurdi *et al.*, 2014) • New resonant peak can be produced (Abbad, 2016)

3. Quarter wave resonator

Quarter wave resonator, also called side branch, is well known for its reactive silencing capability. One of the most unique features of this resonator type is its simple design, which only consists of a tube that is physically mounted on a main duct or a pathway. Due to its simplicity the quarter wave resonator can be easily placed in a number of different ways inside a system, as shown in Fig. 9 (Herrin *et al.*, 2014). As the name suggested, the resonator's tube length is a quarter of the sound wavelength that it is designed to abate. This concept is based on the standing wave phenomenon in a closed tube, where the quarter wavelength entering the tube will be reflected off at the end of the tube and self interfering, hence it will be attenuated. Only the wave that fits in with the tube will resonate, while other frequencies are lost, hence this explains the resonator's narrow frequency bandwidth.

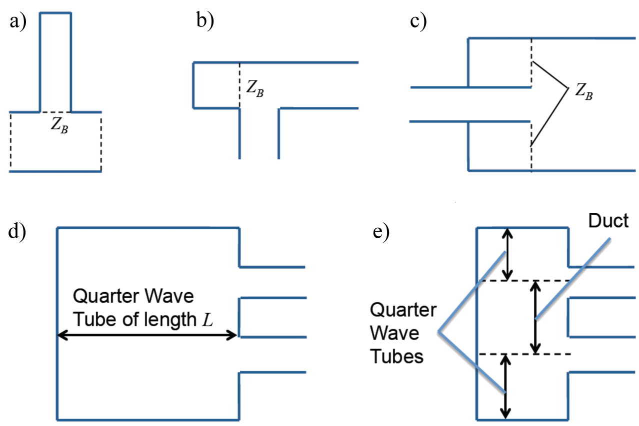


Fig. 9. Different configurations for quarter wave tubes: a) off main duct; b) at a turn; c) as an extended inlet or outlet; d) flow reversal chamber with quarter wave tube length; e) flow reversal chamber with two quarter wave tubes (Herrin *et al.*, 2014).

The fundamental frequency, f_r of the quarter wave resonator goes with the following formula:

$$f_r = \frac{c}{4l}. \tag{2}$$

In the formula, l is the tube length [m] and c is the sound speed [m/s].

Many interesting studies on quarter wave resonator have been carried out recently. Howard and Craig (2014b) investigated several orifice geometries of quarter wave resonator to determine which was the least affected by the high speed exhaust gas passing over the resonator. Three side branch geometries were studied; a sharp edge, a backward inclined branch, and a bell mouth. Experimental testing was conducted using all three configurations of quarter wave tube geometries which were attached to the exhaust of a large diesel engine that was loaded by a water brake dynamometer. The results showed that the side branch with the bell mouth opening produced the greatest noise reduction and hence was the least affected by the gas flow past the side branch with the highest noise reduction measured at 36 dB for engine speed of 1700 rpm and 140 kW load, as shown in Fig. 10. It was suggested that this occurred due to the bell mouth design with the lowest resistive acoustic impedance as compared to the other geometries. Tang (2012) investigated the acoustic effects of one or more narrow quarter wave resonators flush mounted in a long infinite duct wall. Apart from the sound transmission loss properties of a single wall mounted array, double arrays resonators configured symmetrically about the duct axis were also examined. FEM was used to compute the wave propagation characteristics. The simulation results suggested that the transmission losses of the arrays, whether single wall mounted or arranged in double arrays on opposite duct walls, are high whenever resonance occurred along a particular quarter wave tube, excluding the last two arrays. The author suggests that this is most probably due to the combined effect of the monopole radiation of the resonating tube and the dipole like action of the two consecutive tubes immediately downstream of the resonating one. Noise reduction at the non resonant frequencies can also be observed, explained by the expansion chamber effect, and this phenomenon appeared to be more prominent in the cases of symmetrical arrays. It was also demonstrated that the system was able to provide a wide sound reduction band, up to 17 dB with an appropriate quarter wave resonator length arrangement.

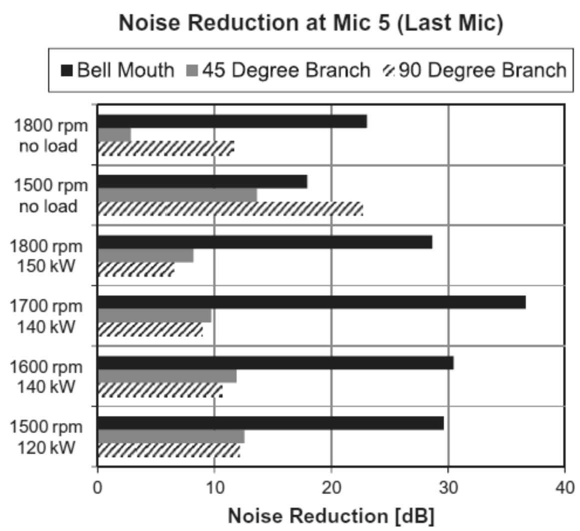


Fig. 10. Noise reduction measured downstream of the side branch (Mic 5) forvarious engine speeds and loads (Howard, Craig, 2014b).

Wang *et al.* (2016) further studied sound propagation in a duct with a quarter wave tube array installed flushed periodically. The underlying sound wave interaction of the setup was analysed by the transfer matrix method, and then validated by numerical simulation. Two configurations of tube array were investigated. One is the quarter wave tube array with identical length and the other one is the quarter wave tube array with the progressively tunedlength. In both cases, the distance between two quarter wave tubes was set constant, thus the tubes were mounted periodically along the duct. From the results it can be seen that with the case of identical tube length array a broad attenuation band at a low frequency can be achieved by properly tuning the periodic distance. While for the case of tubes with varying lengths the results suggested that when these tubes of similar resonant frequencies are placed in close proximity, they may interact degradedly and result in a drop of the overall performance, as shown in Fig. 11. However, this issue may be eliminated by appropriately tuning the periodic distance to two times the length of the longest tube. In addition, this technique also extended the stopband to lower frequencies. The low frequency sound interactions between coupled narrow side branch arrays installed in an infinitely long rectangular duct are investigated numerically using FEM by Yu and Tang (2017). The interactions between the coupled side branch arrays produce both dipolelike and quadrupolelike radiations into the main duct. The results show that the coupling of two side branch arrays of different side branch length series one next to another on one side of the duct wall can enhance the performance in terms of spectral uniformity of sound transmission loss compared to the single array cases. The installation of two coupled arrays on opposite sides of the duct cross section results in improvement of the magnitudes of the transmission loss in general. But reversing the side branch arrangement of one of the coupled arrays was found to be detrimental to the attenuation performance of the array system at low frequencies.

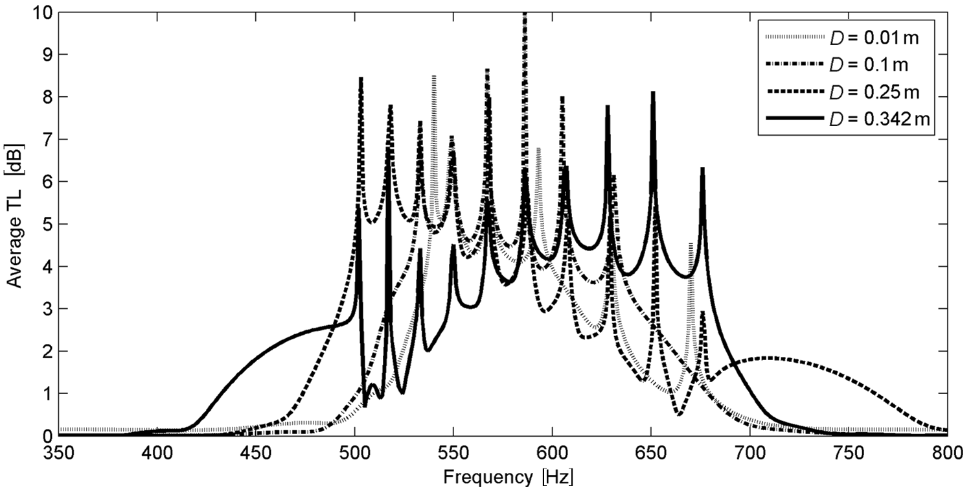


Fig. 11. Average TL of tubes of varying lengths with different periodic distance. Dotted line: $D = 0.01$ m; dashed dotted line: $D = 0.1$ m; dashed line: $D = 0.25$ m; solid line: $D = 0.342$ m (Wang *et al.*, 2016).

Chiu (2014) proposed a "hybrid side branched muffler", targeted to efficiently reduce the peak noise level, and also considering a space constrained situation. The "hybrid side branched muffler" is a combination of silencer elements, which are expansion chamber, dissipative muffler, and array of parallel side branch elements. A numerical analysis using a simulated annealing (SA) method was adopted and two kinds of SA control parameters (*kk*, *iter*) were found to be important, which influenced the solution's accuracy during SA optimization process. The results revealed that the peak values of pure tones were efficiently reduced after the hybrid side branched muffler was added. It was found that with increasing the number of the parallel side branch resonators, the noise elimination performance of the muffler grows as well due to widening the attenuation frequency band. The results also showed that mufflers with both reactive and dissipative elements can simultaneously attenuate noises at both lower and higher frequencies, hence improving the silencer's performance as a whole with overall noise reduction increment up to 40.6 dB.

The adaptive quarter wave resonator concept was examined by Howard and Craig (2014a). They experimented with the resonator's functionality using recorded in duct reciprocating engine exhaust noise. The control system used an innovative approach of determining the phase angle of the transfer function between the microphones in the quarter wave tube and the main duct by adopting sliding – Goertzel algorithm. From the calculations, the microprocessor generated appropriate control signals to the motor controller which was connected to a linear actuator. This linear actuator is the one responsible for moving the piston in the quarter wave tube, which explains how the adaptive quarter wave resonator system works.

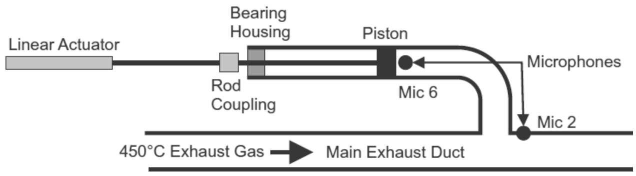


Fig. 12. Schematic view of the exhaust system and the adaptive quarter wave tube (Howard, Craig, 2014a).

Figure 12 illustrates the scheme of the exhaust system and the adaptive quarter wave tube. The experiment was conducted by attaching the adaptive quarter wave tube directly to the exhaust system of a large diesel engine. The system used in the study was designed as robust and able to withstand diesel exhaust gas which contains soot and whose temperature may reach over 450°C. Several cases were studied. The first case – a with constant engine speed, and the second case – with the engine speed step changed. It follows from the results that the adaptive quarter wave tube demonstrates its ability to eliminate noise at the fundamental and third harmonic of the engine firing frequency, thus the system transmission loss as a whole was enhanced. The system also showed the ability to adapt to changes in the engine speed, exhaust gas temperature, and load applied to the engine, as well as providing high noise attenuation over a wide range of frequencies. The collected data showed that the adaptive quarter wave resonator was able to maintain more than 20 dB noise reduction for varied loads of 190 kW to 70 kW and varied exhaust gas temperature 340°C to 460°C. The study proved that sliding Goertzel algorithm could be used successfully in a control system to estimate the phase angle. Table 2 shows the variation of the quarter wave resonator and its characteristics.

Table 2. Variation of quarter wave resonator and its characteristics.

Muffler's type	Characteristic
Quarter wave resonators in array	• Proper tuning of periodic distance can widen sound attenuation band, especially at a low frequency (Tang, 2012; Wang *et al.*, 2016).
Hybrid side branched muffler	• Increasing number of parallel side branch resonators widen the attenuation band (Chiu, 2014) • Combine reactive and dissipative elements simultaneously, attenuate noise at both lower and higher frequencies (Chiu, 2014)
Adaptive quarter wave resonator	• Able to produce high noise attenuation over a wide frequency range (Howard, Craig, 2014a)

4. Other muffler configurations

Apart from the two widely known resonators – Helmholtz resonator and quarter wave tube – there are also other types of mufflers' configurations in use that were studied for their noise attenuation capabilities. They may not be favoured due to their complex design, high manufacturing cost, or any other factors. However, they also show a promising acoustic performance, and studies might suggest their use in certain related fields. This kind of mufflers includes Herschel-Quincke (HQ) tube, helicoidal resonator, and other custom design silencers.

4.1. Herschel-Quincke

Liu and Yin (2011) studied the Herschel-Quincke (HQ) tube concept for noise reduction in circular ducts with and without the mean flow. Herschel-Quincke tube is basically a bypass duct with both of its ends connected to the main duct for sound attenuation purposes. For their study, numerical simulations were performed using GT-Power software, in order to understand the effects of the bypass duct angles and diameters towards its acoustics characteristics. The results show that the angle has basically no impact on the sound transmission loss of HQ tube in the case with no flow. However, varying HQ diameters would produce a significant impact, as the larger the tube diameter, the broader noise reduction reported, while the diameter of the bypass duct was kept smaller than the main duct diameter. The results of HQ of 80 mm diameter show an increase in TL about 5 dB in average for 0 to 1000 Hz frequency range with the maximum difference up to 18 dB compared to its 25 mm HQ diameter counterpart. The transmission loss variation with the mean flow was found to be more complex than the transmission loss without the flow. In the case with the mean flow, the amplitude and band of the noise reduction varied along the changes of the angle, where 120° bypass duct angle demonstrated the best attenuation performance. Alonso *et al.* (2013) proposed two adaptive concepts to enhance Herschel-Quincke waveguides' capabilities. Passive HQ waveguides are used to provide noise reduction in ducts at desired narrow frequency bands associated with their resonances. In order to enhance the attenuation performance of HQ, two adaptive concepts – the ball-in and the deflecting diaphragms – have been developed and further investigated analytically and experimentally, as shown in Fig. 13. According to the results, the application of HQ waveguides, which is commonly restricted due to its narrow sound reduction band capabilities, was extended to applications that aim at variable frequency. For the waveguides using a ball-in HQ tube, the results showed frequency adaptation of single resonances up to 400 Hz for the absolute frequencies range below 2500 Hz. In contrast, the diaphragm system did not show the same adaptation performance. From the findings, the suggested concepts have a potential to be further studied and fine tuned for applications with the tonal noise of variable frequency.

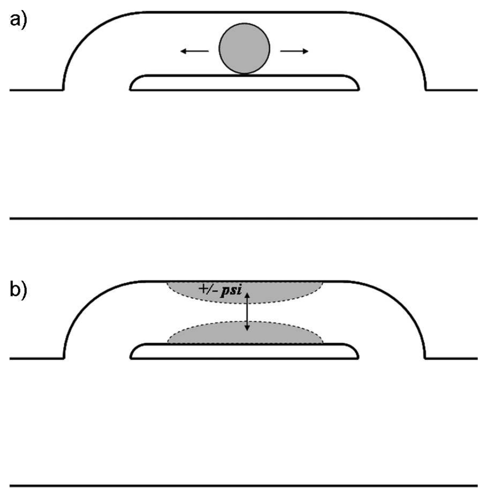


Fig. 13. Schematic view of the adaptive HQ tubes using the (a) ball and (b) diaphragm devices (Alonso *et al.*, 2013).

4.2. Helicoidal resonator

Łapka (2014) examined the sound propagation and fluid dynamics through circular ducts with a spiral element inside which is also known as helicoidal resonator, shown in Fig. 14. A numerical analysis of transmission loss and pressure drop of acoustic helicoidal resonators was presented with a constant pitch to cylindrical duct diameter ratio and different number of helicoidal turns (n). The range of helicoidal turns from 0 to 2.0 was examined for acoustic modelling. The results showed that the specific sound attenuation band of helicoidal resonators with ratio $s/d = 1.976$ existed almost for all investigated cases. But the most exciting part of transmission loss started from about $n = 0.4$ and ended for about $n = 1.0$. For all the cases, the pressure drop was found to increase with the increase of the mean air volume and velocity. The biggest and almost linear increase of pressure drop takes place for the numbers of helicoidal turns in the range from 0.1 to about 0.6. From 0.6 to 1.0 the pressure drop rises nonlinearly.

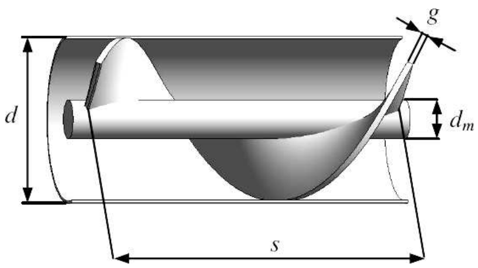


Fig. 14. Schematic view of helicoidal resonator.

4.3. Various approaches

Apart from the previously mentioned methods, there are still other sound attenuating approaches that we may classify separately as a unique group. Karlsson and Glav (2007) proposed the usage of flow reversal resonator for duct noise attenuation. In order to lower resonator's fundamental frequency, one of their suggestions is to acoustically short circuit the inlet and outlet duct of the resonator. Such a configuration will resemble a Helmholtz resonator in the low frequency range, but with a choked flow through the short circuit, wider attenuation band may be achieved as the main flow will be forced through the expansion chamber. The theoretical model for the concept was developed and then compared with real experiment results. Basing on the results it can be observed that the flow reversal resonator produced broader attenuation bandwidth compared to traditional side branch resonators. The concept then was further tested and successfully implemented in a truck silencer. Even at a high flow speed, 0.15 Mach number, the silencer demonstrated reasonable noise reduction above 20 dB for most of the part at a low total pressure loss penalty as shown in Fig. 15. Duan (2008) presented a variable volume resonator concept using an adaptive control mechanism. He applied the transfer matrix method to evaluate acoustic performance of the proposed mechanism. The results show that by increasing the expansion ratio (area ratio of the expansion chamber to the connecting tube), transmission loss can be improved significantly with peak frequencies remaining unchanged. By increasing the area ratio of the expansion chamber from 15 to 25, the TL has improved about 10 dB at resonant peaks. The authors also suggested the method of searching the global TL maxima to improve the system transmission loss while using adaptive piston to manipulate the chambers' volume. However, experimental study is needed to further validate this work.

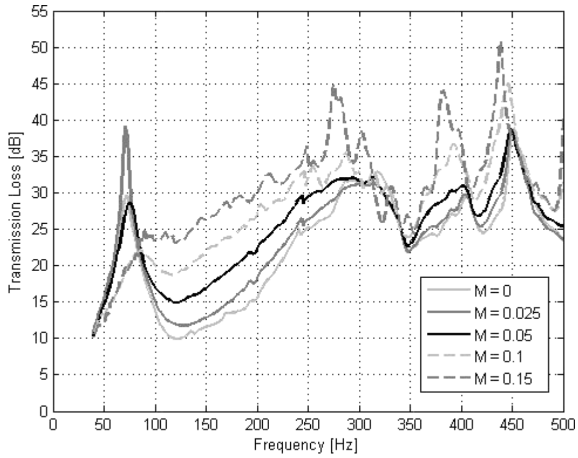


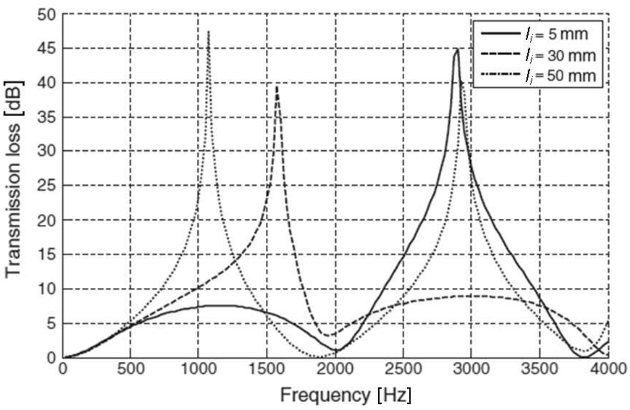
Fig. 15. Transmission loss at varying Mach number for the truck silencer (Karlsson, Glav, 2007).

Huang (2009) introduced a novel noise attenuation concept which consists of side branch cavities filled with a light gas and covered by two membranes as two apertures. This mechanism causes incident waves to be scattered by the membranes into two paths, one through the central duct and another through the cavity bypass, hence, is expected to produce a unique acoustic characteristics. The results showed that with appropriate tensile stress the trough between the two spectral peaks can be highly improved and the low density of the cavity gas filling was identified to be the critical factor. The introduced new system was even able to obtain above 10 dB transmission loss at the trough between two resonant peaks. The study also suggests that the acoustic performance of the new resonator is comparable with and even exceeds that of the drumlike silencer with the same cavity geometry. The system's transmission loss result presents two peaks, unlike the three peak spectrum seen in the drumlike silencer. However, the very short aperture length demonstrated by the proposed silencer suggests that the required membrane tension is much lower than in such drumlike silencer. Wang and Huang (2012) proposed a new duct silencing device based on the mechanism of the human middle ear. The system named 'ossicular silencer' consists of two rigid endplates connected by a single rigid rod, with all three pieces placed in a side branch cavity. The concept was investigated numerically with a 2D FEM to observe its acoustic potential. From the simulation results it can be observed that broadband sound attenuation was achieved in the very low frequency region. Two or more resonant peaks appeared with the transmission loss between two neighbouring peaks kept at a high level, above 10 dB. In contrary to other reactive silencers, not the cavity volume but its length was found to be the crucial parameter in the design of the ossicular silencer. When the cavity length increases, significant sound reduction can be seen at very low frequencies. The study also suggests that the fluid medium in the enclosed cavity acts like an added mass. However, its stiffness effect was found to be insignificant.

Chiu (2010) analysed the sound transmission loss optimisation of three chamber side mufflers with a perforated tube under a space limitation. The four pole system matrix model and simulated algorithm were used to evaluate their acoustic performance. The results showed that for a single chamber muffler, the overall noise reduction is 6.7 dB, while, for the two chamber muffler it is 40.1 dB. As expected, the three chamber muffler hybridised with a perforated tube demonstrated the best overall noise reduction up to 46 dB. The study suggested that both the chamber and internal tube play important roles in reducing the system noise level. It was also found that the perforated tube mechanism showed a better noise reduction than that of the non perforated tube. Guo and Tang (2017) studied the concept of a resonator with the perforated intruding inlet (PII) as an effective silencer element. In this work, both a 1D and 2D transfer matrix methods were developed to predict the transmission loss of the resonator without considering the mean flow and then the results were validated with an experimental test. A few resonators' configurations were selected and tested to analyse the effects of the structure parameters for transmission loss. From the results, as shown in Fig. 16, it was found that by increasing the length of the inlet extension, the resonant frequency of such a resonator decreased and more resonant peaks appeared. At the same time, a higher perforation rate leads to a shift of the resonant peak towards higher frequencies. Other than that, the study suggested that reducing the inlet/outlet radius can further enhance the system's TL without affecting the frequency of the resonant peak.

Ouédraogo *et al.* (2016) explored wave propagation through a circular duct with non local lining using circular multi cavity muffler. The liner concept uses perforated screens backed by air cavities with the cavities' dimension selected to be of the order or larger than the wavelength, so that acoustic waves within the liner could propagate parallelly to the duct surface. This produces complex scattering mechanisms among duct modes, which causes the muffler to be more effective over a wider frequency range. The results sug-

a)



b)

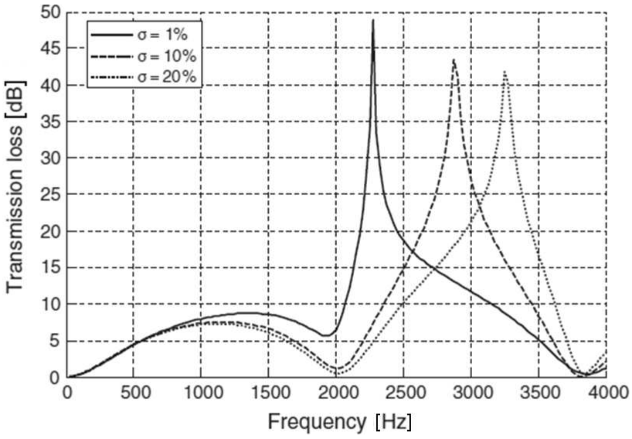


Fig. 16. TL of resonators with different: a) length of inlet extensions; and b) perforation rate (Guo, Tang, 2017).

gest that assuming equipower distribution with random phases, when the cavity depth is set fixed, partitioning along the axial direction demonstrates a much stronger effect on transmission loss spectra than along the azimuthal direction. A muffler configuration of 4×4, which is one of the variations on cavity size along the axial direction, produced an improved TL curve with two resonant peaks above 20 dB. Shi and Mak (2017) probed on the sound propagation in a periodic array of micro perforated tube mufflers. A micro perforated panel (MPP) is composed of a thin plate with submillimetric size holes which are distributed across its surface. The Bloch wave theory and the transfer matrix method were adopted to study the wave propagation and in good accordance with FEM simulation and experimental results. From the results, the MPP muffler has shown a similar sound elimination performance to the traditional dissipative muffler when having the same muffler size. MPP mufflers performed better than the single MPP muffler in terms of the peak transmission loss by 28 dB increment and the effective attenuation band by achieving a higher TL in a broader frequency range. When compared to the directly connected MPP mufflers, the maximum transmission loss of the three periodic MPP mufflers may increase at the resonant frequency peak but this depends on the periodic distance between the mufflers. Thus, the best muffler configuration will be based on the designer silencer optimisation target of the resonant peak and effective frequency range.

While Erol and Meriç (2009) studied the effect of a resonator with a combined characteristics of Herschel-Quinke, Helmholtz resonator, quarter wave resonator, and expansion chamber, while playing with its geometries such as the side branch diameter. A transfer matrix method was established to predict the transmission loss of the system and showed good agreement with FEM. The results indicate that increasing the diameter ratios of side branch duct to the main duct can widen the transmission loss frequency bandwidth. It was also observed that with adding resonators such as Helmholtz resonator and quarter wave resonator, additional TL peaks appear in other frequencies. The major effect of varying the length of the expansion chamber lies in shifting the TL peak frequencies of the system. Table 3 demonstrates different muffler configurations and their features as discussed in the chapter.

It is interesting to observe how acoustic study on resonator and muffler configuration has been developed in the recent years. Various numerical methods and different silencing approaches were implied to obtain improved system's noise reduction capability. From the studies, we can also see how different types of resonators produce their own unique acoustic characteristics and may also differ in their best suited applications. One will need to acknowledge the significant

Table 3. Variation of the muffler configuration and its characteristics.

Muffler's type	Characteristic
Herschle-Quincke	• Bypass duct angle of HQ only affects TL in the case with the mean flow (Liu, Yin, 2011) • Larger bypass duct diameter produces a broader noise reduction band (Liu, Yin, 2011) • Resonant peaks of the system can be manipulated using waveguides (Alonso *et al.* 2013)
Helicoidal resonator	• Produces transmission loss at high frequency (above 1000 Hz) with the spiral dimensions; can be fine tuned for specific targeted frequency range (Łapka, 2014)
Flow reversal resonator	• Broader attenuation bandwidth compared to traditional side branch resonator even with the mean flow (Karlsson, Glav, 2007)
Variable volume resonator	• Increasing the expansion ratio improves the system's transmission loss across frequencies without changing the resonant peaks (Duan, 2008)
Covered side branch cavities filled with light gas	• Able to maintain high transmission loss between two resonant peaks (Huang, 2009)
Ossicular silencer	• Produces broadband sound attenuation in a very low frequency range (Wang, Huang, 2012)
Three chamber side muffler with perforated tube	• Higher number of chamber side muffler produces better noise reduction performance (Chiu, 2010)
Resonator with perforating intruding inlet	• Increasing inlet extension length can reduce resonator's resonant frequency (Guo, Tang, 2017) • Higher perforation rate shifts the resonant peak towards higher frequencies (Guo, Tang, 2017)
Circular multi cavity muffler	• Can act as expansion chambers, thus causing broadband noise reduction (Ouédraogo *et al.*, 2016)
Micro perforated panel mufflers	• Show similar sound elimination performance as compared with traditional dissipative muffler of the same size (Shi, Mak, 2017) • By adding the quantity of this MPP muffler, higher and broader TL can be achieved (Shi, Mak, 2017)
Hybrid muffler	• Broadband noise reduction can be achieved with fine tuned resonant peaks (Erol, Meriç, 2009)

impact given by the development in resonator study to the advancement of applied fields of acoustics such as automotive, aerospace engineering, and industrial applications.

5. Conclusion

Resonators and mufflers have been key features in reducing duct noise especially in high SPL applications such as automotive and aerospace. This paper provides comprehensive information on types of resonators, muffler modifications, and their comparative acoustic performance. Besides that, the recent advancement in resonator and muffler configurations was discussed in great depth. A substantial study has been done on this topic and it shows promising signs for future developments. However, considerable inputs are still needed in the following areas:

- Numerical model development for Helmholtz resonator with flexible membrane.
- Experimental validation on the spiral neck Helmholtz resonator concept.
- Acoustic characteristic study of parallel coupled resonators.
- Fluid dynamic study for pressure loss effect of multiple resonators array.
- Exploring the adaptive resonator concept in theory and applications.

Finally, the study on resonator and muffler acoustics can play an important role in reducing machineries noise from being released to the environment. Environmental noise has been one of the major environment pollution factors identified by the World Health Organization (WHO) (Fritschi, Brown *et al.* 2011) and through proper study and implementation of resonators and mufflers we can filter noise from its main sources thus providing a better living environment for everyone.

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