Ultrathin Muffler with Coherent Coupling Weak Resonance for HVDC Converter Station Medium Frequency Band Noise Control

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Abstract. HVDC converter station noise is mainly in medium frequency band, but the thickness of the conventional duct silencers are equivalent to the working wavelength, which makes them difficult to apply in narrow spaces. In this paper, through parallel and serial coupling of imperfect Helmholtz resonators with interpolated neck, a hybrid silencer with broadband perfect absorption is presented, which remain above 10 dB from 568 to 992 Hz with a thickness less than 20mm. In order to reveal the underlying physical properties and acoustic performance, simulations considering the coupling of acoustics and thermodynamics and impedance analysis are performed, showing a good consistency, and it’s further verified by experimental result. The results of research can help design effectively, ultra-thin and wide-band duct silencer for HVDC converter station medium frequency band noise control.

1. Introduction

The function of HVDC (High Voltage Direct Current) converter station is to rectify high voltage alternating current into direct current. It is mainly composed of converter transformer, thyristor valves, side filters and cooling equipment. It has been reported that the main noise of HVDC converter station is medium and high frequency band, and the audible noise may exceed 105 dB(A) [1-3]. Because the heating, ventilation and air conditioning system needs to absorb fresh air from outside of the service buildings. Due to the limitation of the size of the ventilation units and the high requirements for the fresh air volume, the possibility of using sound absorbing material and sound insulation device is limited [4]. Therefore, a thin, wide-band sound-absorbing, and easy-to-install duct silencer is urgently needed. [5].

At present, the energy absorption type and energy reflection type silencers can be used to control duct noise [6]. Traditional porous sound-absorbing materials require their thickness to be equivalent to the wavelength of the sound, which makes them very bulky when absorbing low-frequency noise, so they are often used to absorb mid-frequency and high-frequency noise [7-9]. In order to control low-frequency noise, resonance type sound absorbers are often used, such as membrane absorbers [10], Helmholtz absorbers and Fabry-Perot absorbers [11-12]. In the past few years, the above-mentioned resonance-based sound absorbers have been given a new concept, namely, acoustic metasurface, which is a kind of artificial acoustic material with ultra-thin thickness.[13]. Recently, acoustic metasurface has developed into an emerging field, and a large number of researchers have invested in it, making it possible to achieve near-perfect absorption at deep sub-wavelength thicknesses. Ma et al. used a thin ultrathin membrane metasurface structure to form a hybrid resonance to absorb sound.
energy and convert it into electrical energy [14]. N. Jimenez et al. constructed a periodic horizontal slit loaded by identical Helmholtz resonators to achieve perfect absorption through critical coupling [15]. Although certain achievement has been made, most of these resonance-based acoustic metasurface sound absorption bands are relatively narrow, and some researchers have done some research on this problem. Yang et al. proposed a design strategy based on causality relation and designed a 10.86cm-thick structure to achieve perfect absorption of frequencies above 400Hz [16]. Zhang et al. proposed a three-dimensional, single-port labyrinth crimped acoustic metamaterial to perfectly absorb low-frequency noise [17].

To increase the frequency range of low-frequency absorption, a common solution is to combine multiple units that perfectly absorb sound at different frequencies. [18]. However, in these designs, due to the strict limitation of the perfect sound absorption of the unit cell, it also limits the coherent coupling effect and increases its thickness. To overcome these shortcomings, we proposed a silencer model that couples multiple imperfect sound-absorbing units, thereby realizing compact broadband pipe sound absorption in a narrow space.

In this work, we theoretically investigate and experimentally validate an ultra-thin broadband duct silencer consisting of multiple array Helmholtz resonators with embedded apertures (HREAs) to broaden the absorption bandwidth at a deep subwavelength thickness in the low-middle frequency band. The thickness of the proposed duct silencer is only 1/30th of the working wavelength. Although the sound absorption effect of each unit cell is not very good, by appropriately adjusting the coherent coupling effect between imperfect units, they can achieve perfect absorption of broadband together, which reveals the mechanism of the duct silencer with broadband and high sound insulation.

2. Simulation and experiment

A silencer structure, as shown in Fig. 1, is specially designed for the noise reduction problem of medium frequency broadband of duct in narrow space. In order to overcome the shortcoming of the narrow frequency band of the single HREA, we adopt array silencers with different resonance frequencies on the wall of duct. The specific performance is the combination of the different height of the cavity and the different length of the neck.

As is illustrated in Fig. 1(a), the basic unit of the designed silencer is the common HR with different height of the inserted neck. The interior pattern of HREA can be determined by cavity height of the \(i\)-th unit \(h_i\), and the length of neck \(d_i\). The detailed parameters are shown in Table 1. The wall thickness \(t\) and the neck width \(w\) were kept 1mm as constant, meanwhile, the length of cavity \(L_1\) was also kept 39mm as constant. The neck is in the middle of the cavity and \(s = L_1/2\). The whole silencer structure consists of 10 resonators with different height of cavity and different length of neck. Fig. 1(b) shows the schematic of the silencer of exterior length \(L_2\), which was kept as 401mm. The side length \(L_d\) of the square duct is 100mm, in other word, the width of the silencer is 100mm, too.

| Parameters      | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|-----------------|---|---|---|---|---|---|---|---|---|----|
| Cavity height(mm)| 15| 16| 16| 17| 18| 18| 19| 19| 19| 20 |
| Neck length(mm)  | 3 | 4 | 5 | 5 | 5 | 6 | 7 | 8 | 9 | 9.5|

Figure 1. (a) Schematic diagram of the HR unit. (b) The 3D model of the duct silencer.
Finite element (FE) simulations were performed by using COMSOL Multiphysics 5.4 to obtain transmission loss curves and sound pressure distributions. The walls of resonators and duct were set to a hard boundary condition. The sound absorption is mainly due to the thermal viscous effect of the duct, while other silencing mechanisms do exist. The incident pressure $p_0 = 1$ Pa. The material parameters are $\rho_a = 1.205 \text{kg/m}^3$, $\rho_P = 1160 \text{kg/m}^3$, $c_a = 343 \text{m/s}$. Here, the parameters of $\rho_a$ and $\rho_P$ refer to the densities of air and PLA, respectively, $c_a$ represent the acoustic velocities in the air.

Next, we conduct experiments in a home-made impedance tube to verify the results. The experimental device is shown in Fig. 2(a), the side length of the square impedance tube is 100 mm, and the cut-off frequency is 1.7 kHz. The testing apparatus consists of four 1/4-inch B&K microphones (Type 4958A), B&K LAN-XI acquisition hardware (Type 3160-A-042), and a power amplifier (Type LP838). Figure 2(b) shows two samples of 3D printing, the printing material is polylactide (PLA), and the printing accuracy is $\pm 0.1 \text{mm}$.

The 3D printing samples were packed into two metal back cavities and placed symmetrically on the top and bottom of the duct. The gap between the duct and back cavity was sealed with plasticine, as shown in Fig. 2(a) red box. The measured results comparing with theoretical derivation and numerical simulation are plotted in Fig.2(c).

The results show that the prediction results, the simulation and the experiment results are in good agreement, so the reliability of current model silencer is validated through experiment. It is noticeable that there is some discrepancy among simulation and experiment curves around frequency 960 Hz. According to the analysis later, the TL peak corresponding to 960 Hz should be the resonance peak of the HREA unit with the cavity height of 15 mm, but we can see that it is not shown on the experimental curve. The reason for this phenomenon may be that the size error of the first cavity, which leads to its resonance frequency deviation. For other frequencies, the difference is mainly due to the energy dissipation mechanism. The damping effect is not considered in the simulation, which must exist in the actual equipment. The inconsistency between the numerical results and the analysis results is mainly due to two aspects. On the one hand, the length in the theoretical model is approximated by a geometric shape. However, the numerical model takes into account the actual geometry, which may cause differences in the approximate length correction used in the theoretical model. On the other hand, the theory holds that the influence of evanescent waves caused by change in HREAs and duct interfaces is not fully considered here, but only the plane wave hypothesis. The numerical model takes this effect into account, so this may also cause some differences.

![Figure 2](image)

**Figure 2.** (a) Experimental setup. (b) Samples fabricated through 3D printing. (c) Comparison of theory data, simulation data and experiment data.

### 3. Analysis and discussion

As shown in Fig. 3(a), compared with a single TL, the total TL has an additional effect. It can be seen that when 10 HREA units are coupled to form a silencer, the TL curve of the silencer has only three obvious peaks, and more peaks are coupled together to form a larger TL. As you can see, the TL peak frequency of each HREA unit is 558, 586, 614, 645, 702, 748, 771, 796, 856 and 964 Hz.
respectively. Although each individual HREA unit only has a TL peak at its own resonant frequency and the peak value is less than 10dB. When all ten units are coupled, the ten peaks can merge together into a broad stopband, with frequencies ranging from 568 to 992 Hz. The reason why 10 dB is chosen is mainly based on the Ref. 19. The thickness of the sample is much shorter than the central wavelength of the stopband \((h/\lambda = 0.033)\). At the same time, we can find that when multiple resonant units are coupled, better wideband noise attenuation can be achieved between imperfect units due to their coherence.

**Figure 3.** The characters of the duct silencer. (a) The TL of the duct silencer and the 10 individual component HREAs respectively. (b) The absorption coefficient of the duct silencer and the 10 individual component HREAs respectively. (c) The normalized impedance of the duct silencer. (d) The absorption spectrum of the unit1 as a function of the diameter \(w\).

In order to help us understand the working mechanism of the muffler, we analyzed the sound absorption coefficient of the structure (Fig. 3(b)), and the average sound absorption coefficient (A) reached 0.9 in the range of 568-878 Hz. But it is not difficult to find that the absorption effect of a single unit cell (color line) is poor, which shows that the coherent coupling effect can enhance the overall absorption ability [20]. At the same time, the overall thickness of the metasurface, compared with the lower limit frequency of 568 Hz, is only 1/30th of the deep subwavelength scale. Besides the analysis on the absorption coefficient, such a model can be analyzed by its acoustic impedance \(Z\) [21]. It is known that impedance matching with the medium \((\rho_0 c_0)\) can achieve perfect sound absorption, where the impedance matching means that \(Z_s = Z/\rho_0 c_0 = 1\), and \(Z_s\) is the normalized impedance to air. This is equivalent to \(Re(Z_s) = 1\) (resistance matching) and \(Im(Z_s) = 0\) (reactance matching). Within the stopband of the model, the acoustic resistance and reactance curves of the model fluctuate around 1 and 0 respectively, which means continuous impedance matching (Fig. 3(c)). By comparing Fig.3(a) and Fig.3(b), we notice that the stopband is 568 to 992Hz, so the transmission coefficient(T) should be less than 0.1 in this frequency band \((TL = -10 \log_{10} T)\). However, the band (A ≥ 0.9) is significantly narrower at the high frequency of the stopband. In the frequency band above 878Hz, the mismatch with the air impedance results in strong reflection. It is the reason why in the frequency from 878Hz to 992Hz, though the absorption coefficient is gradually decreasing, the TL is still high \((TL \geq 10dB)\).

Because the width of the neck of each unit is very small \((w = 1mm)\), the small machining error will also have a great impact on its resonance frequency. Thus, we have also further investigated the balance by tuning the geometrical parameter(\(w\)) of the unit1 and the corresponding absorption spectra are illustrated in Fig.3(d). It is found that as \(w\) gradually increased from 0.8mm to 1.2mm, the peak frequency of absorption coefficient also increased from 506Hz to 606Hz. Meanwhile, due to
impedance mismatch, the peak value of the absorption coefficient of unit 1 can only reaches 0.5, which corresponds to the purple line in Fig.3(b). We can find another design method from Fig.3(d), that is, in addition to the previous parameters, we can also realize broadband absorption by adjusting different w of several units.

4. Conclusion

In this work, we have successfully designed a duct silencer with HREAs that maintains a transmission loss greater than 10 dB in the frequency range of 568 to 992 Hz, and its thickness is less than 20 mm. The numerical analysis of the designed model is validated by theoretic and experimental results. Although the absorption coefficient and TL value of each HREA were not high, we obtained a kind of metasurface type duct silencer with a bandwidth greater than 300Hz (A ≥ 0.9) by using the coherent coupling effect. Such design provides a new idea to reduce the medium wideband frequency of the duct noise in the narrow space for HVDC converter station.

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