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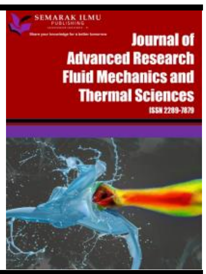

Numerical Modeling and Geometry Enhancement of a Reactive Silencer

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ABSTRACT

Internal combustion engines and blowers frequently utilize silencers to reduce exhaust noise. In the current paper, the transmission loss of reactive silencers is predicted using the plane wave decomposition method and a three-dimensional (3-D) time-domain computational fluid dynamics (CFD) approach. A mass-flow-inlet boundary condition is first used to perform a steady flow computation, which serves as an initial condition for the two subsequent unsteady flow computations. At the model's inlet, an impulse (acoustic excitation) is placed over the constant mass flow to perform the first unstable flow computation. Once the impulse has fully propagated into the silencer, the non-reflecting boundary condition (NRBC) is then added. For the scenario without acoustic excitation at the inlet, a second unsteady flow computation is performed. During the two transient computations, the time histories of the pressure and velocity at the upstream measuring points as well as the history of the pressures at the downstream measuring point are recorded. The related acoustic quantities show variations between the two unsteady flow computational findings. As a result, the transmitted sound pressure signal is just the sound pressure downstream, while the incident sound pressure signal is obtained by utilizing plane wave decomposition upstream. The transmission loss (TL) of the silencer is then calculated after the Fast Fourier Transform (FFT) converts the two sound pressure signals from the time domain to the frequency domain. The numerical calculations and the reported data are in good agreement for the published results, in addition to geometry enhancement by increasing number of holes in the cross section for muffler.

1. Introduction

Internal combustion engines and blowers frequently utilize silencers to reduce both their intake and exhaust noise. The acoustic attenuation performance measurement and analysis are vital for silencer design that works well. The performance of silencers' acoustic attenuation can be predicted using both time-domain and frequency-domain techniques. The fundamental benefit of the time-domain method over the frequency-domain method is the ability to account for the effects of complex gas flow and viscosity on noise propagation and attenuation in silencers. As a result, the behavior of silencers' acoustic attenuation may be accurately predicted. The transmission loss of

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reactive silencers was evaluated, one-dimensional (1-D) time domain finite difference method was devised, and the impacts of numerical dissipation and dispersion on the method's acoustic predictions were examined by Dickey *et al.,* [1].

Comparison research was carried out in order to determine how well various solutions to the 1-D gas flow equations performed when utilized to estimate the frequency response of exhaust mufflers. Their findings offer suggestions for an appropriate numerical scheme selection that takes the mesh spacing into account by Broach *et al.,* [2].

Three Dimensional CFD time-domain model was used to investigate the TL of the expansion chamber and reversing chamber. In the absence of airflow, their predictions were in good agreement with the measured data and FEM predictions. Evidently, the experiment does not support the calculated TL at a low Mach number flow by Broach *et al.,* [3].

In addition, the Three-Dimensional time-domain CFD technique was used to calculate the TL of perforated tube silencers both with and without the flow and their predictions in the targeted frequency range are in good agreement with the results. Additionally, they looked at the effects of flow velocity and temperature on the effectiveness of perforated tube silencers as acoustic attenuators and discovered that the flow velocity close to the perforation is incredibly anisotropic and nonhomogeneous. The above-mentioned studies are based on the numerical simulation of the impulse method of TL measurement; therefore, the main drawback is that the inlet is quite lengthy and that a computational model is needed to distinguish between the incident and reflected signals. As a result, the computational domain is expanded and there are more discrete grids overall. To achieve a complete numerical solution, a sizable computing effort and period of time were required. In order to analysis complicated acoustic networks by Ji *et al.,* [4,5].

An approach based on the linearization of the finite volume method was presented by Torregrosa [6] who uses elements with zero-dimensional analogues to describe the three-dimensional cavities. This approach is then extended to basic but relevant three-dimensional geometries in the absence of mean flow, exhibiting good agreement with experimental and other computational results.

The integrated 1D, multi-D, and quasi-3D techniques were introduced to predict the TL of reactive and dissipative mufflers for the numerical simulations of complicated shape silencing systems. The potential of both the hybrid 1D-3D code and the quasi-3D code with respect to a straightforward, fully 1D model has been demonstrated by studying reverse chambers with enlarged inlets, outlets, and perforates. It is important to accurately capture multidimensional wave effects at mid- and high-frequency ranges, as well as the impacts of high amplitude disturbances and mean flow, according to a comparison between TL predictions and experimental measurements. The non-reflecting boundary condition (NRBC) could be applied at the inlet and outlet boundaries to improve computation efficiency and lower calculation expenses introduced by Montenegro *et al.,* [7].

The NRBC was used to analyses the acoustic attenuation properties of a rectangular muffler without mean flow in the combined 1-D and 3-D simulations. The incident signal, however, was obtained by the use of an additional simulation in which the silencers were substituted by a straight pipe. Even though the NRBC produced some minor false reflections, the numerical calculations and experimental measurements below 1000 Hz were closely consistent by *Torregrosa et al.,* [8].

A predictive method was proposed to determine the transmission loss of reactive silencers using the three-dimensional (3-D) time-domain computational fluid dynamics (CFD) approach and the plane wave decomposition technique and it was found that the numerical results agree well with experimental measurements by Zhu *et al.,* [9].

A study of a gasoline engine's exhaust noise level at various operating speeds is presented. The noise level is under the acceptable ranges due to the progress and development of vehicles emission reduction, which is from 41 Db to 59 Db by Al-Qdah [10].

A reflecting double-expansion chamber muffler was created on a lab scale for the current study using equations. The acoustical performance of the developed muffler was then examined using a 4-microphone approach and an impedance tube to estimate TL. the manufactured muffler gives the needed TL for exhaust chambers, as evidenced by the acquired TL 27.5 dB and the required TL 25 dB by Damyar *et al.,* [11].

The current study aimed to enhance muffler geometry for model that demonstrated in Zhu *et al.,* [9] powered with flow graphs illustrating the change what happens for pressure & noise upstream & downstream and checking the lengths of the inlet and outlet connecting tubes by study the effect of increasing number of holes on muffler performance which increase the transmission loss when the porosity of inner tube increased to 11%.

2. Methodology

The TL of a silencer is calculated as the difference between the sound power level that enters the silencer ($L_{w_{in}}$) and the sound power level that is transmitted from the silencer ($L_{w_{tr}}$) with an anechoic outlet termination. The TL is written as by Munjal [12] in mathematics.

$$\mathrm{TL} = \mathrm{L}_{\mathrm{w_{in}}} - \mathrm{L}_{\mathrm{w_{tr}}} \tag{1}$$

If the harmonic plane waves propagate in the inlet and outlet tubes of the silencer, the TL may be rewritten as follows

$$\mathrm{TL} = 10\log_{10}\left(\left|\frac{p_1^+}{p_2^+}\right|^2\right) + 10\log_{10}\left(\frac{S_i}{S_o}\right) \tag{2}$$

Where $p_1^+$and p_2^+ are the incident and transmitted absolute waves respective sound pressures. The cross-sectional areas of the inlet and outlet tubes, respectively, are denoted by S_i and S_o. The transmitted and incident sound pressures can be represented as follows using the plane wave decomposition

$$p_1^+ = \frac{1}{2}(p_1 + \rho_0 c u_1) \tag{3}$$

$$p_2^+ = p_2 \tag{4}$$

where p_1 and u_1 are the sound pressure and particle velocity at the cross-sections of the inlet, respectively, c is speed of sound and p_2 is the sound pressure at the cross-section of the outlet. The TL of the silencer can be simply computed using equations once p_1, p_2 and u_1 are obtained by Eq. (2), Eq. (3) and Eq. (4)

2.1 Computational Domain

Model geometry were established as shown in Figure 1 and its dimensions mentioned in Table 1.

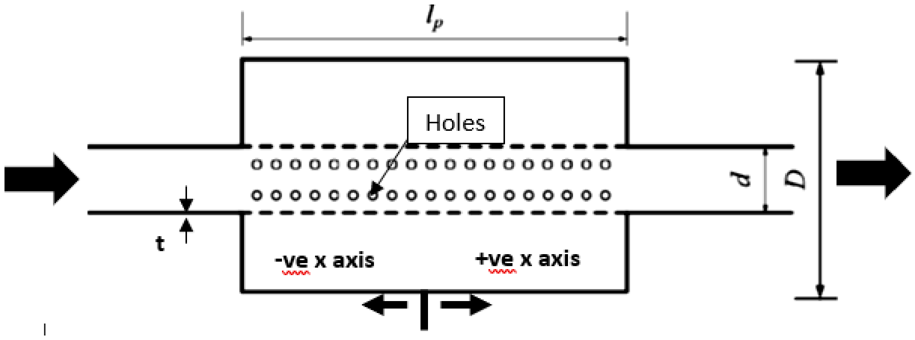

Fig. 1. Main construction of the silencer

Table 1
Whole dimensions of the silencer

l_p	200 mm
d	32 mm
D	110 mm
Hole diameter	*6 mm*
The porosity of the inner cylinder	*9 %*
Inner cylinder thickness (t)	*2mm*

2.2 Numerical Details

Using double-precision as the data type, the full-flow equations are solved using the commercial package tool ANSYS-Fluent 19.2 Bhattacharyya [13]. The selected numerical solver is a second-order implicit transient formulation pressure-based, segregated implicit solver. The second-order upwind spatial discretization is used to solve the equations for mass, momentum, energy, turbulent kinetic energy, and turbulent dissipation rate. The measurements of both static pressure and axial velocity may converge after around ten rounds for residuals of 10^{-5}. The maximum number of iterations per time step is set at 50 in order to obtain the appropriate residuals. The SIMPLEC (Semi-Implicit Method for Pressure-Linked Equations-Consistent) algorithm is the basis of the pressure-velocity coupling system. The realizable k-Ɛ turbulence model is applied when there is flow Ali Shehab [14] and Ariffin [15]. In the numerical simulation, air is utilized as the working medium, and an ideal gas density is assumed. Engineering handbooks list additional physical factors that rely on temperature.

2.3 Boundary Conditions

The mass-flow-inlet boundary condition for the stable calculation is established using the mass flow rate per unit area of 41 kg/(s.m^2), at 0.1 Ma, at the computational model's velocity inlet. The outflow surface is specified as having a constant air pressure of zero gauge, while the backflow pressure parameter is static pressure in the two unsteady simulations. At the intake and output boundaries, the reflected pressure waves from the silencer were absorbed using a large computational domain size. The wall in the computational model is assumed that it's stationary and no slip wall. In addition, the impact of viscous shear stress is considered while the wall's heat transfer is disregarded. Despite using only one-quarter of the model, due to symmetry, two monitoring points were established as shown in Figure 2, were used in the current study. l_1 = 10 mm and l_2 = 17 mm are the distances between the silencer's endplates and the monitoring positions, respectively. These separations correspond to those found in the experiment of Lee *et al.,* [16].

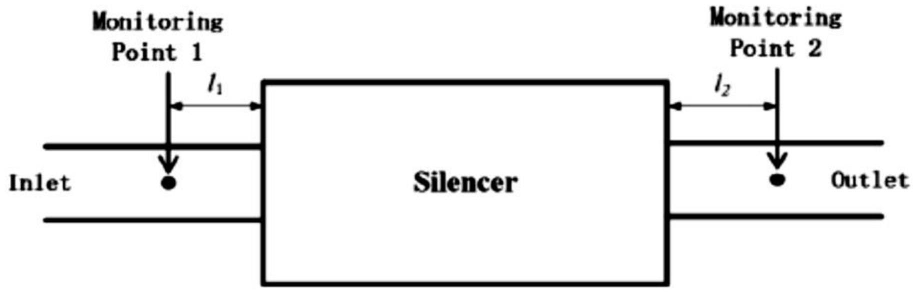

Fig. 1. Boundary of the model and location of the monitoring points

2.4 Domain Independency Study

The length of the inlet and outlet tubes was examined against the static gauge pressure along the longitudinal axis of the model. Six different computational domains were generated for domain independency test. The length of inlet and outlet pipes is different from 0.5L (100 mm) to 3L (600 mm). Figure 3 shows the static pressure distribution along the longitudinal axis passing through the pipe centerline. The stability of the results is dependent on the convergence of the pressure reduction across the silencer chamber (p_1/p_2). Where P_1 is the sound pressure at monitoring point 1, and P_2 is the sound pressure at monitoring point 2. Table 2 shows the error analysis of the domain independency test by comparing the value of pressure reduction in each case. Numerical results of cases 4, 5 and 6 are nearby the same with error less than 2%. The length 2L was used in the present work for both inlet and outlet pipes to reduce the time of numerical solution.

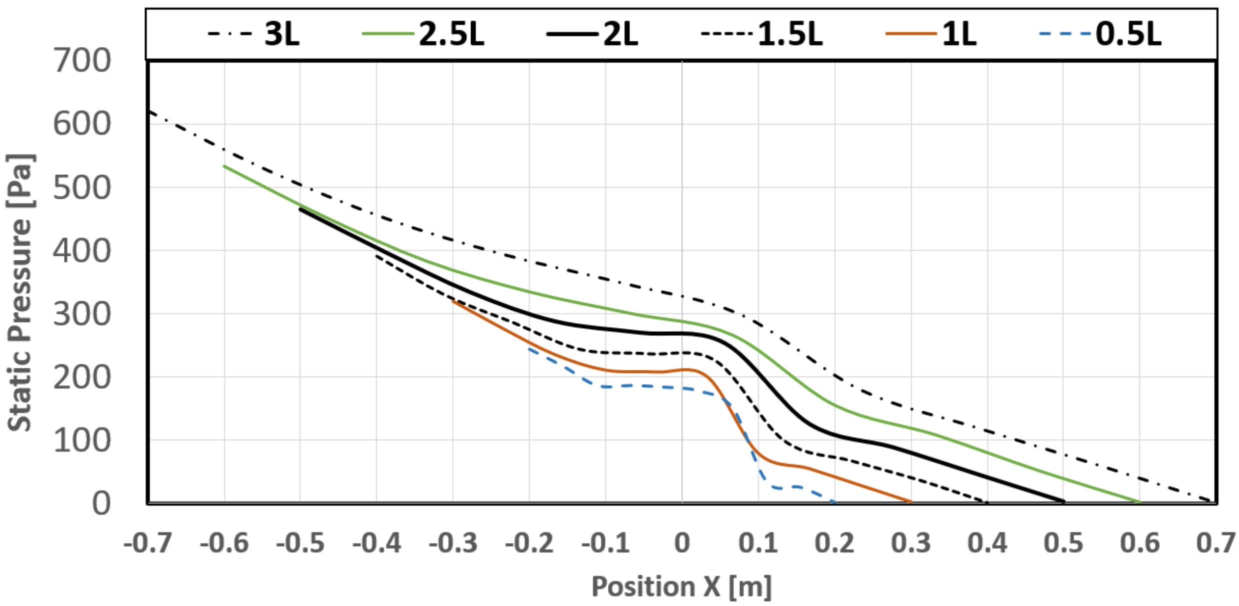

Fig. 2. Domain independency test of the model L=200mm)

Table 2
Error analysis of the domain independency test

Case	Computational Domain	Gauge Pressure p1 [Pa]	Gauge Pressure p2 [Pa]	p_1/p_2	Error [%]
1	0.5 Lp	185	35	5.2857	56.9
2	1 Lp	205	90	2.2778	32.6
3	1.5 Lp	230	150	1.5333	14.1
4	2 Lp	270	205	1.3171	1.92
5	2.5 Lp	310	240	1.2917	0.85
6	3 Lp	365	285	1.2807	-

Accordingly, the domain lengths of inlet and outlet connecting tubes are chosen as 400 mm in the present works which are longer than those used in [3–5].

2.5 Grid Independency Test

In the present works, the numerical model is discretized with hybrid grids with tetrahedron unstructured mesh. The maximum cell size Δ*S* of the unstructured mesh in the perforated region was tested in this section. Two techniques were used in the discretization process in this model. First, using an inflation layer near the perforated part of the silencer and the walls. Second, determining the maximum cell size inside this region. Six cases were generated in the test, the maximum element size is different from 2 mm to 0.2 mm. Figure 4 shows the static pressure distribution along the numerical model centerline in each case. Calculations of error in each case have been added to this study based on the pressure drop divided by the base value of pressure in the followed case. Table 3 shows the error analysis of this grid independency study by comparing the pressure drop (p_1-p_2) in each case. The maximum cell size selected is 0.5 mm with smaller error 1.5%, with total number of elements 1M, for the unstructured meshes in the perforated region, as well as the inlet and outlet connected tubes.

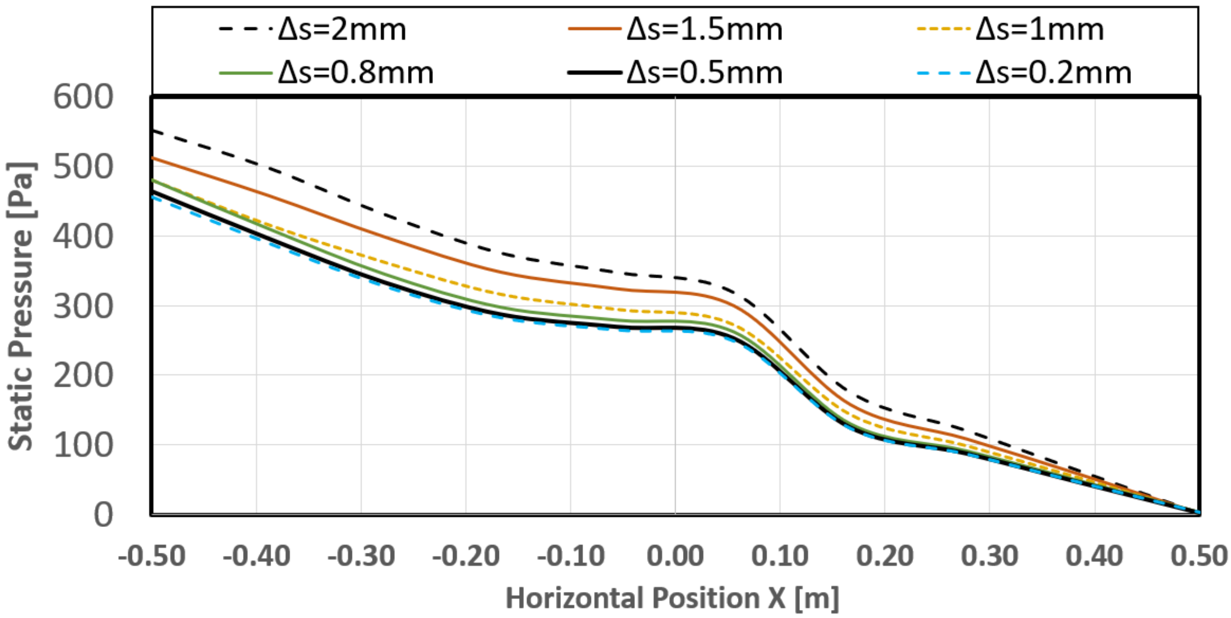

Fig. 3. Grid independency study (L=200mm, domain 2L, total length of the model 5L=1m)

Table 3
Error analysis of the grid independency study

Case	Min Element Size	Elements No.	p_1 [Pa] Gauge	p_2 [Pa] Gauge	(p_1-p_2)	Error [%]
1	Δs=2.0 mm	640K	385	265	120	20
2	Δs=1.5 mm	735K	340	240	100	17.6
3	Δs=1.0 mm	875K	300	215	85	25
4	Δs=0.8 mm	940k	275	207	68	4.6
5	Δs=0.5 mm	1000k	270	205	65	1.5
6	Δs=0.2 mm	1450K	268	204	64	-

Moreover, for the regions with seven gradients such as the central perforated tube region and areas near the perforated holes, the mesh needs to be further refined to capture the complex flow phenomena. The denser grid in the refined region is achieved by increasing the grid layers along the thickness direction of the perforated tube. Namely, the perforation regions may have much smaller mesh size and thus the regions connected to the perforations are also refined through grid automatic matching as shown in Figure 5.

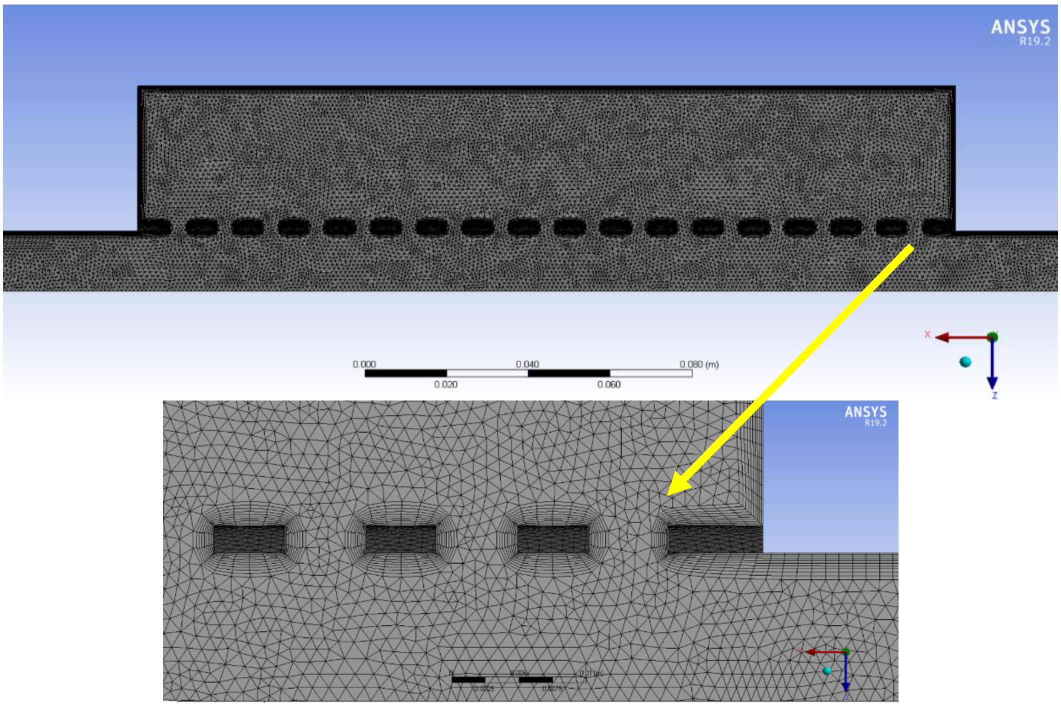

Fig. 4. The unstructured grid of the silencer model

2.6 Validation of the Numerical Results

The numerical model in the present work was validated against published experimental data by [9]. A steady solution is generated first with the same operating condition, after convergence of the solution, a transient model is subjected with time step size 5x10^{-6} which recommended by [9]. The acoustic model is activated, the acoustic data (sound pressure, sound pressure spectra, and sound power) were monitored at the defined location P_1 and P_2. The time domain of the sound pressure variation at each point is converted to the frequency domain using Fast Fourier Transform FFT model. Figure 6 and Figure 7 show the time domain of the pressure at points 1, 2 respectively.

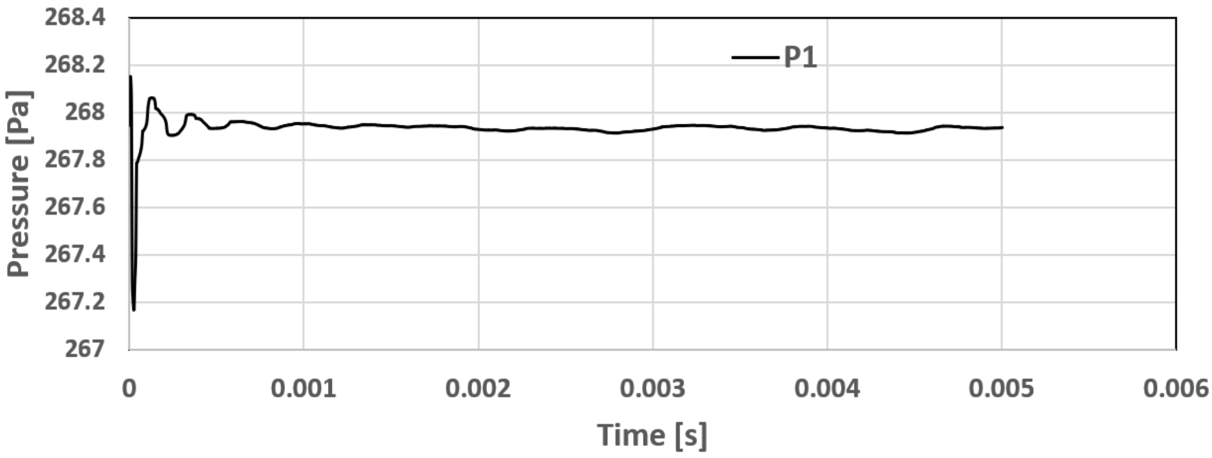

Fig. 5. Time history of the pressure at point 1

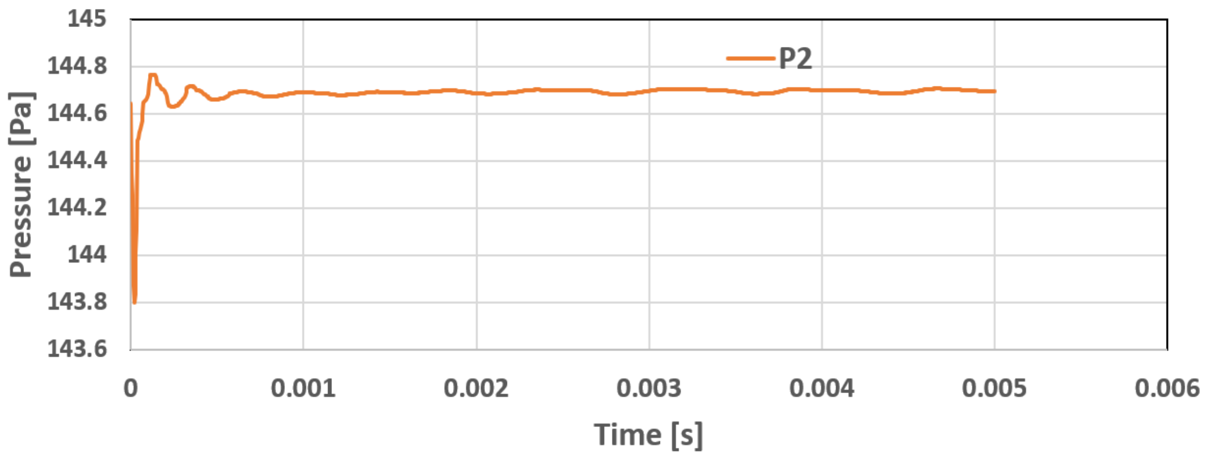

Fig. 6. Time history of the pressure at point 2

The time domain is transmitted to the frequency domain for both P_1 and P_2, then equation (2) is used to determine the transmission loss TL.

The validation of the present numerical model is shown in Figure 8. The numerical results agreed with the experimental data.

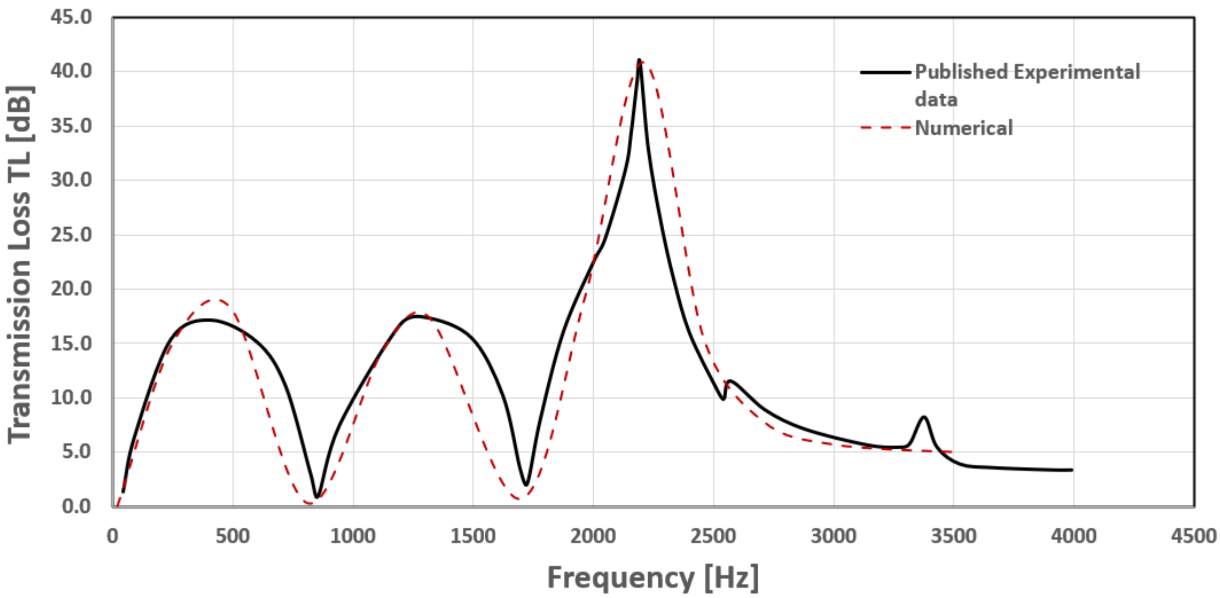

Fig. 8. Validation of the numerical model (L=200mm)

The current model provides a useful data to examine the effect of geometrical parameters on the behavior of the silencer.

The study the effect of increasing number of holes along ether inner cylinder on the pressure drop will be illustrated in the next section.

3. Results and Discussion

3.1 Effect of Increasing Number of Holes in the Transverse Direction

In this section, the number of holes in each section will be increased to 6 instead of 4. The total number of holes is 102. The pressure distribution across the horizontal.

In addition to studying another case with 8 holes in each section where the porosity at each case will be illustrated as the Table 4.

Table 4
Illustrating Porosity % with different number of holes

Number of holes in each section	Total number of holes along cylinder	Porosity (%)
4 Holes	68	9 %
6 Holes	102	11 %
8 Holes	136	18 %

As shown in Figure 9 the pressure drops increase with increasing number of holes per section till 6 holes but after that the increasing number of holes becomes inefficient.

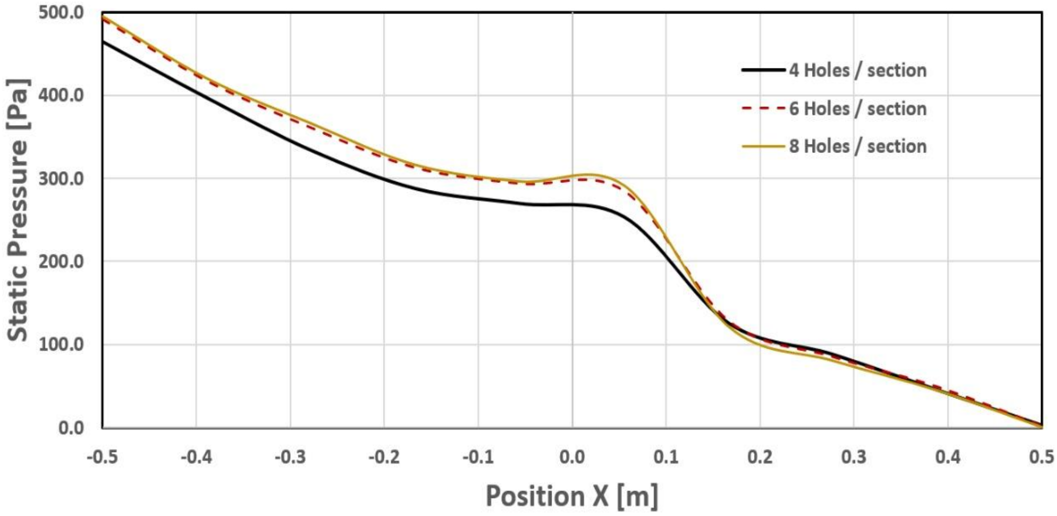

Fig. 9. Illustrating the effect of number of holes in transverse direction on pressure drop

3.2 Effect of Increasing Number of Holes in the Longitudinal Direction

In this section, the number of holes in the longitudinal direction will be increased to 19 instead of 17. The total number of holes is 76. The pressure distribution across the horizontal axes is shown in Figure 10.

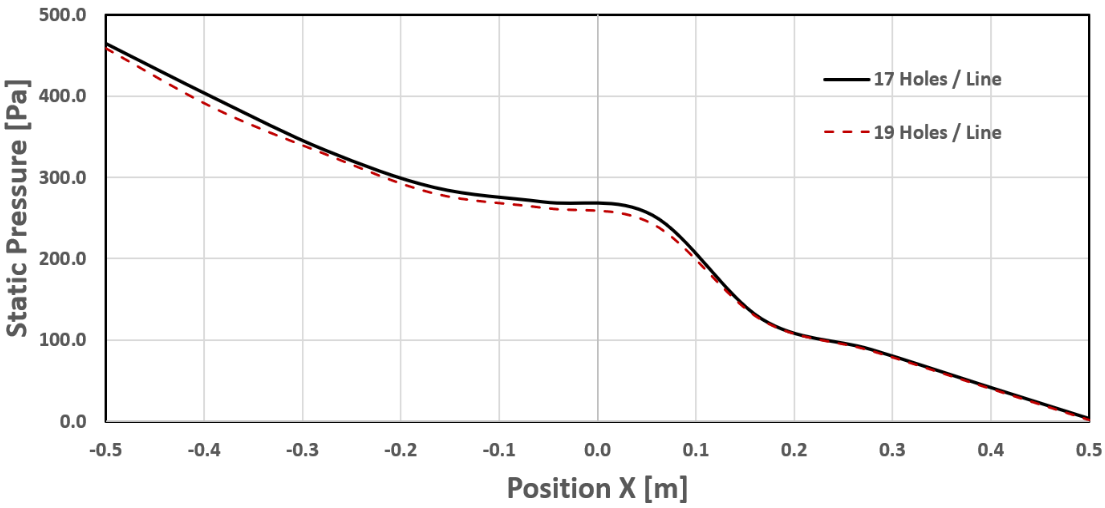

Fig. 10. Illustrating the effect of number of holes in longitudinal direction on pressure drop

The pressure drop is not affected with increasing number of holes in the longitudinal direction comparing with increasing number of holes per section.

4. Conclusions

A prediction numerical approach employing the 3-D time domain combining the non-reflecting boundary condition and plane wave decomposition technique is proposed to evaluate the TL of reactive silencers with considerations of complex gas flow and viscous dissipative influences. Straight-through perforated silencers with and without flow are projected to have different TLs. The comparisons show that the numerical results and measurements coincide well, demonstrating the efficacy of the suggested strategy. Four different cases were proposed in this paper by changing the number of holes in both directions; longitudinal and transverse, the CFD simulation of the impulse method of TL measurement shows that adding holes to the tube section causes the TL to rise. But beyond 6 holes per section, this becomes inefficient, and adding further holes in a longitudinal orientation is useless on TL.

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