Analysis of Reactive Muffler by Boundary Element Method and Experimental Method

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Abstract— The exhaust systems of internal combustion engines generate noise with a wide frequency range, including particularly strong low frequency components. In such applications, silencers can be designed to work at low frequencies by reactive acoustic elements such as Helmholtz or quarter wave resonators, terms used in reactive muffler design. Mufflers play an important role in reducing the exhaust and intake system noise and as a result, a lot of research is done to designing these systems effectively the acoustic performance of reactive muffler is investigated. New regulations and standards for noise reduction and emission compel the automobile industries to make some improvements in design of muffler for attaining desired noise reduction. The work focuses on the design of a new muffler for an agricultural tractor with the aim of containing the noise within the limits given by international standards. Further, the design modifications are to be verified for noise reduction by COMSOL Multi-physics software.
Keywords: Backpressure, COMSOL Multi-physics Muffler, Transmission Loss

I. Introduction

A. *Muffler:*

Internal combustion engines are typically equipped with an exhaust muffler to suppress the acoustic pulse generated by the combustion process. A high intensity pressure pulse generated by combustion in the engine cylinder propagates along the exhaust pipe and radiates from the exhaust pipe termination. Measurements of the exhaust pipe pressure pulse on an engine shows that the majority of the pulse energy lies in the frequency range of 0-4000 Hz. Exhaust mufflers are designed to reduce sound levels at these frequencies [2].

B. *Types of Muffler:*

Despite the terms and myriad of configurations, the silencer can be broken into three fundamental types:

1) Absorptive (dissipative)
2) Reactive or Reflective
3) Combination of Reactive and absorptive.

There are a number of methods currently used to model and investigate the performance of mufflers.

1) Analytical Method:
2) Transfer Matrix Method (TMM):
3) Numerical Method:
4) Boundary Element Method:
5) Experimental method for measuring TL

II. Boundary element method

The boundary element method (BEM) is an important technique in the computational solution of engineering or scientific problems. In applying the boundary element method, only a mesh of the surfaces is required, making it easier to use and often more efficient that the more common finite element method. The boundary element method (BEM) is a powerful tool in computational acoustic analysis. The Boundary Element Method in Acoustics serves as an introduction to the BEM and its application to acoustic problems and goes on to complete the development of computational models. Boundary element methods are developed for three important classes of acoustic or Helmholtz problems: modeling the acoustic field either interior or exterior to a closed surface or carrying out an acoustic modal analysis [5].

III. Evaluate TL for Simple Expansion Chamber Muffler in SYSNOISE by BEM:

SYSNOISE is an FEM/BEM based computational acoustics program that allows users to input a geometry, impose boundary conditions, select environmental parameters, and solve the system of resulting equations in one, two or three dimensions. Once the system has been solved, a host of post-processing options are available to determine the various performance characteristics. Using command line code, it was possible to perform the calculations for all three methods, utilizing both FEM and BEM, and in both two and three dimensions.

IV. Principle Steps of Boundary Element Application

1) Model Definition
   - Meshes
   - Model Type
   - Acoustic Properties
   - BC: source, vibrating panels
   - Advanced Boundary Conditions
2) Use of BEM solvers
3) BEM applications
4) Post processing

V. Analysis in COMSOL by BEM:

A typical TL calculation using SYSNOISE has the following steps Model-1 – Acoustic Harmonic BEM

1) Mesh on surface only
   - field-point mesh for other results
2) Direct BEM solver

- closed geometry
- fluid on one side: interior or exterior

3) Indirect BEM solver
   - no restriction on geometry
   - open
   - ribbed
4) fluid on both sides: interior and exterior

5) Surface absorbers

VI. CALCULATION OF TL

It is a reasonable speculation that the frequency at which the TL would be maximum is at the acoustic modes of muffler. The analysis is an integral step during the calculation of TL using BEM. The acoustic modes of the muffler could be obtained by performing a BEM analysis in COMSOL. This analysis is performed only to obtain a better understanding of the system behavior. The acoustic FLUID boundary element analysis consists of the following steps:
Mass density = 1.225 kg/m3
Sound velocity = 340 m/sec

– Apply impedance boundary condition on the open faces using the equation

$$Z = \rho c\left(0.24(ka)^2 + j(0.56ka)\right) \quad (4.9)$$

$$k = \frac{2\pi f}{340}$$

a= radius of pipe

VII. EXPERIMENTAL ANALYSIS FOR MEASURING TL OF SEC MUFFLER

A. *Experimental Se up:*

A schematic diagram of experimental set up for calculating TL of simple expansion chamber is as shown in figure 5.3. It consists of a noise generation system, noise propagation system and noise measurement system. The TL is measured by transfer function method [22]. The set has following main components,

– Impedance Tube
– Data acquisition system
– Noise source with amplifier
– Sound pressure measuring microphones

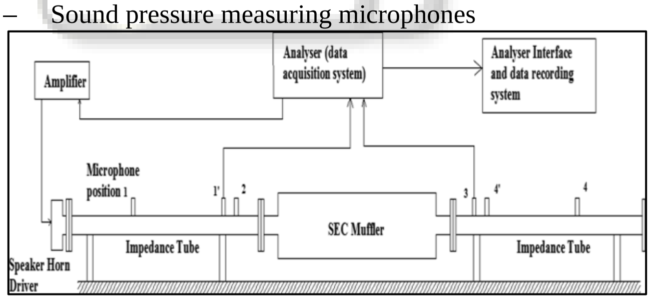


Fig. 1.1: Experimental set up with its components

Impedance tube is a rigid tube through which sound propagates and reflects from simple expansion chamber (test sample) which results in creation of standing waves in it. It has measuring locations (1, 1', 2, 3, 4, and 4') at specific distances from test sample where the acoustic pressure is measured. A sound source device is connected at the one end of impedance tube and test muffler at other end. As we are interested in incident and transmitted wave, two impedance tubes are used either side of the muffler. The main purpose served by impedance tube is providing guidance to sound wave as required for plane wave propagation.

The data acquisition system used is a 4 channel FFT analyzer with an interface package called NV Gate V7.0 for the control and setting of analyzer. It collects the pressure data from microphones and feed it to data recording storage system. It also has a single output channel which fed to speaker through analyzer. A random noise signal is generated in analyzer and play by the speaker. The reason behind using random noise is it contains equal power density of noise for each frequency. Sound source used is of high wattage to produce at least 120 dB of noise. Pressure field microphones are used for measurement. The two microphones are sufficient as transfer function method is used. Transfer function is evaluated for each set of reading. The actual test set up with as component specifications is as shown in figure. Two configuration of set up is used with respect to end conditions here shows one configuration of no load condition.

VIII. SOUND PRESSURE MEASUREMENT AND TL CALCULATION:

Experimentation for pressure measurement mainly consists of analyzer setting and data processing for TL calculation. The experiment is performed for frequency range 50 to 720 Hz. The measurements are taken in two slots with two locations 1-1' and 4-4' as shown in figure 25 respectively to cover desired frequency range [22]. The location 1-2-3-4 is used for measuring pressure in frequency range 50-400 Hz, while the location 1'-2-3-4' is used for measuring pressure in frequency range 400-3400 Hz. The first set of readings is taken for no load condition with both frequency range and same procedure is repeated for with load condition. Two microphones are used for measurement, which are sufficient for measurement of transfer function between sound pressures measured at two locations. One microphone is placed at location 3 and other placed at location 1, 2 and 4 respectively to get transfer function H31, H32 and H34 with respected locations. All other locations except locations where microphone are inserted are sealed with pins to avoid sound leakage. The obtained transfer functions are then directly used in four-pole element calculations to get TL.

A random noise signal is generated with frequency range 10 to 5 KHz with 100% burst. The speaker noise spectrum is kept 10 to 15 dB higher than the background noise for all frequencies of interest which indicates low signal to noise ratio. The loudspeaker is operated for 5 to 10 minutes so that the temperature inside the tube is stabilized. The sound leakage is tested and wax is used to seal these leaks. The precaution is taken while changing the microphone to other location so that it inserted in precise position. Correction to transfer function is added for considering the microphone mismatch.

$$H_c = \sqrt{H_{ij} H_{ji}}$$

$$H_{ij(corrected)} = \frac{H_{ij(measured)}}{H_c}$$

Each reading is taken for time domain pressure signal with a recorder module of analyzer which runs for a period of 100 sec. This data is then post processed with the help of NV Gate V7.0 in FFT module to get frequency domain data [23]. MS OFFICE EXCEL program is used to get TL versus frequency plot for simple expansion chamber. The result is then compared to numerical and analytical and discussed further.

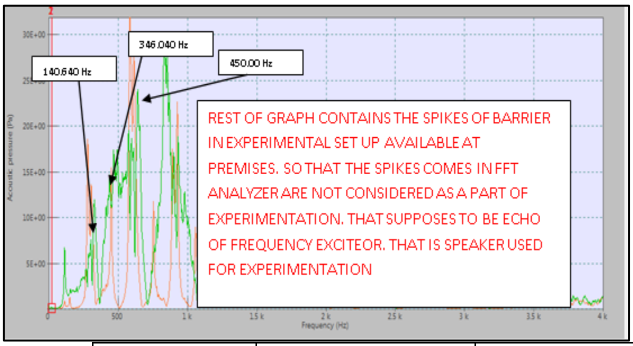


Fig. 8.1: Time Domain Signal Collected by Data Acquisition System for SEC

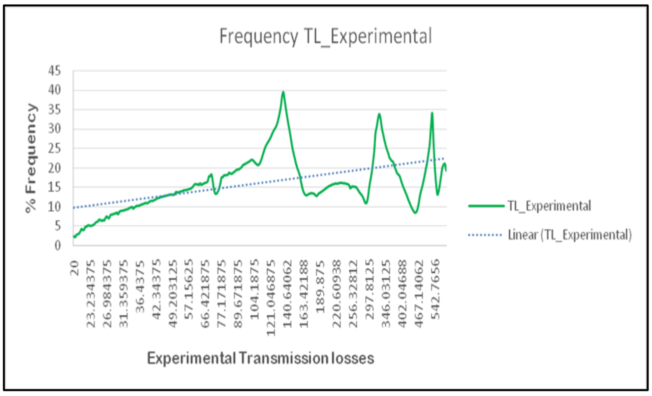
IX. RESULT

Frequency taken for range 0-650Hz. Frequency is decided on the basis of application of muffler which is generally found in farm tractor. (The New Holland)

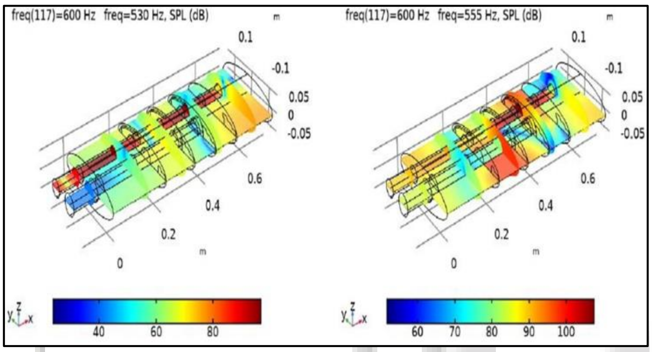
%Frequency	TL_Experimental	%Frequency	TL_Experimental	%Frequency	TL_Experimental
20	2.332015	35.203125	9.95869	62.6875	15.553154
20.21875	2.1152332	35.609375	10.220808	63.421875	15.967464
20.453125	2.73113	36.015625	10.089775	64.15625	15.555305
20.703125	2.859569	36.4375	10.291657	64.90625	15.74896
20.9375	3.058328	36.859375	10.410459	65.65625	15.929905
21.1875	3.5388796	37.296875	10.572682	66.421875	16.088165
21.421875	4.214057	37.71875	10.656089	67.1875	16.170137
21.671875	3.9508808	38.15625	10.820689	67.96875	16.480179
21.921875	4.054378	38.609375	10.934281	68.75	17.714815
22.1875	4.774038	39.046875	10.8265705	69.5625	17.793758
22.4375	4.81535	39.515625	10.998271	70.359375	18.232958
22.703125	5.151127	39.96875	11.303922	71.1875	16.500118
22.96875	5.1334157	40.4375	11.411242	72	14.255324
23.234375	4.976261	40.90625	11.466859	72.84375	13.326154
23.5	5.075908	41.375	11.49626	73.6875	13.304226
23.765625	5.2142563	41.859375	11.707868	74.546875	13.787166
24.046875	5.3977404	42.34375	11.871055	75.40625	14.5475645
24.328125	5.7829037	42.828125	12.115669	76.28125	15.855563
24.609375	6.062803	43.328125	12.177612	77.171875	17.501165
24.890625	6.1473346	43.828125	12.322278	78.0625	17.530533
25.1875	6.6320696	44.34375	12.44003	78.96875	18.02895
25.484375	6.5377088	44.859375	12.5209675	79.890625	18.014221
25.78125	6.28676	45.375	12.585074	80.8125	18.085405
26.078125	6.5149	45.90625	12.706712	81.75	18.19344
26.375	6.4150662	46.4375	12.779393	82.703125	18.687817
26.6875	7.0482583	46.984375	12.843621	83.671875	18.479023
26.984375	7.4553895	47.515625	12.98367	84.640625	18.402908
27.3125	7.050339	48.078125	13.054355	85.625	18.637989
27.625	7.0751166	48.625	13.052511	86.609375	18.889355
27.9375	7.8368855	49.203125	13.07674	87.625	19.16473
28.265625	7.9088364	49.765625	12.993495	88.640625	19.432009
28.59375	7.9972777	50.34375	13.288883	89.671875	19.509233
28.921875	8.192772	50.9375	13.758196	90.703125	19.604162
29.265625	8.192947	51.515625	13.585708	91.765625	19.88562
29.609375	8.44536	52.125	13.653621	92.828125	20.146074
29.953125	8.026618	52.71875	13.812443	93.90625	20.663624
%Frequency	TL_Experimental	%Frequency	TL_Experimental	%Frequency	TL_Experimental
30.296875	8.646944	53.34375	13.856089	94.984375	20.80025
30.640625	8.819008	53.953125	13.964356	96.09375	21.006174
31	8.961977	54.578125	14.173729	97.203125	21.193605
31.359375	8.931589	55.21875	14.220446	98.34375	21.35405
31.734375	9.072207	55.859375	14.2042265	99.484375	21.56262
32.09375	9.168498	56.5	14.366138	100.64062	21.848614
32.46875	9.292866	57.15625	14.446136	101.79687	22.031656
32.84375	9.380183	57.828125	14.536575	102.98437	21.833828
33.21875	9.609084	58.5	14.676138	104.1875	21.462814

33.609375	9.747095	59.171875	14.984406	105.39062	21.122992
34	9.89851	59.859375	15.441655	106.60937	20.80117
34.390625	9.446499	60.5625	15.786862	107.85937	20.642334
34.796875	9.815452	61.265625	15.697202	109.10937	20.931026
111.65625	22.574158	198.84375	14.448359	354.10938	23.798248
112.95312	23.636929	201.15625	14.803175	358.21875	22.619394
114.26562	24.642662	203.48438	14.9476	362.375	22.117884
115.59375	25.526096	205.84375	15.222881	366.59375	21.664032
116.92187	26.125097	208.23438	15.358712	370.84375	21.444628
118.28125	26.668953	210.65625	15.51606	375.15625	20.393314
119.65625	27.203833	213.09375	15.708495	379.5	19.496412
121.04687	27.82192	215.57812	15.721559	383.90625	18.651814
122.45312	28.62276	218.07812	15.904472	388.35938	18.261976
123.875	29.312181	220.60938	15.903385	392.875	17.89598
125.3125	29.886124	223.17188	15.874841	397.4375	16.975029
126.76562	30.425714	225.76562	16.021772	402.04688	15.923413
128.23438	31.232264	228.375	16.051598	406.71875	15.022843
129.73438	32.468166	231.03125	16.080359	411.4375	14.248808
131.23438	33.94241	233.71875	16.035227	416.21875	13.429214
132.75	35.77444	236.42188	15.950819	421.04688	12.675077
134.29688	38.400166	239.17188	15.931337	425.9375	11.7414055
135.85938	39.40497	241.95312	15.81931	430.875	10.983368
137.4375	37.315506	244.75	15.730594	435.875	10.152457
139.03125	35.08343	247.59375	15.541234	440.9375	9.477519
140.64062	33.004387	250.46875	14.698133	446.0625	8.928949
142.28125	31.069487	253.375	15.053739	451.23438	8.449793
143.92188	29.333406	256.32812	15.156465	456.48438	8.472535
145.59375	27.31369	259.29688	15.048749	461.78125	9.005435
147.29688	25.315868	262.3125	15.09464	467.14062	10.351294
149	23.767984	265.35938	14.825068	472.5625	12.323143
150.73438	22.397442	268.4375	14.33912	478.04688	13.905912
%Frequency	TL_Experimental	%Frequency	TL_Experimental	%Frequency	TL_Experimental
152.48438	21.033154	271.54688	13.823547	483.59375	15.070655
154.25	19.88865	274.70312	13.344398	489.20312	16.487404
156.04688	18.999756	277.89062	12.951832	494.89062	18.051466
157.85938	17.988848	281.125	12.407142	500.64062	19.807196
159.6875	16.26765	284.375	11.586338	506.4375	21.413311
161.53125	14.813669	287.6875	10.894395	512.3281	23.74466
163.42188	13.741496	291.01562	10.96919	518.2656	26.079285
165.3125	13.143194	294.40625	12.331059	524.28125	30.658985
167.23438	12.892161	297.8125	14.8945	530.375	33.93978
169.17188	12.967473	301.28125	16.80801	536.53125	26.505081
171.14062	13.212541	304.76562	18.719849	542.7656	20.145329
173.125	13.307517	308.3125	21.273117	549.0625	16.01239
175.125	13.460461	311.89062	24.275679	555.4375	13.129206
177.17188	13.350957	315.51562	28.848951	561.875	13.824461
179.21875	13.337341	319.17188	30.511396	568.40625	15.705186
181.29688	13.042745	322.875	32.561775	575	17.869635
183.40625	12.715802	326.625	33.781452	581.6719	19.972084
185.53125	12.858514	330.42188	32.56243	588.4375	20.774477
187.6875	13.370835	334.25	30.173023	595.2656	20.981428
189.875	13.502717	338.14062	28.678057	600	19.246395
192.07812	13.761244	342.0625	27.149208		
194.29688	13.956118	346.03125	25.849848		
196.5625	14.256449	350.04688	24.660732		

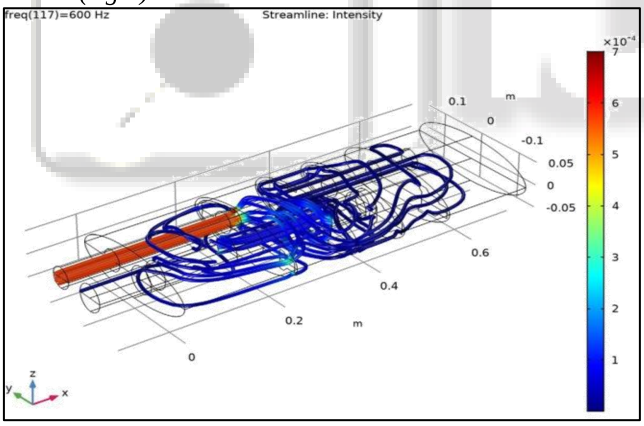
A. Frequency Vs TL losses in experimental analysis graph



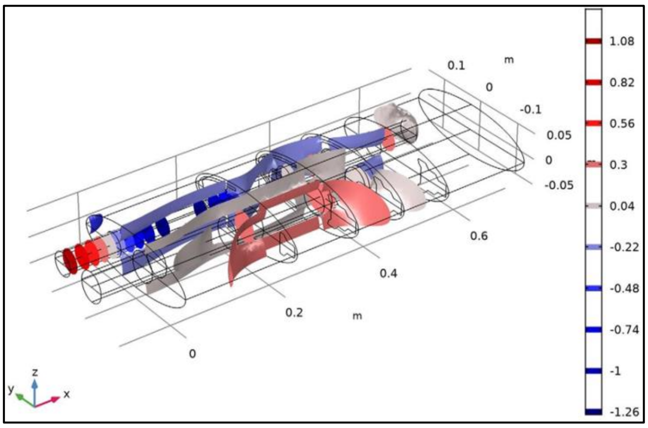
B. Validation of experimental readings with software readings and comparison



1) Sound pressure level distributions at 530 Hz (left) and 555 Hz (right)



2) Streamline plot of the acoustic intensity field. The color scale represents the magnitude of the acoustic intensity vector



3) The last default plot, depicting pressure isosurfaces should look like the figure above

C. Graph comparison of Actual Vs Computed.

Comparison of actual experimental result to simulation created in COMSOL5.2

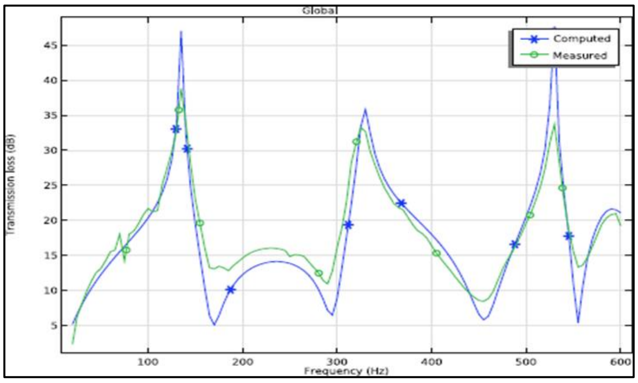


Fig. 9.3.1: Transmission loss versus frequency: model simulation results and experimentally measured values.

X. CONCLUSION AND FUTURE SCOPE

A. Conclusion:

Based on work carried out in this project, it can be concluded that:

1) We computationally investigated the acoustical performance of a reactive muffler i.e. TL of simple expansion chamber, which consist of baffles with same cross section. As we can see that after 100Hz – 580Hz sound propagation get started dying out. The pick point observed in experimental analysis around 120Hz – 150Hz and after that in consisting interval 350Hz-450Hz & 450Hz – 650Hz.
2) The variation between the computed analysis and measured experimental analysis is about approximately 7% of all data analyzed. The actual variation is 6.83%.

B. Future Scope:

The present study has revealed some of the things that can be of interest and can be executed in future:

1) The experimental set up can be improved further for better surface finish, avoiding the leakage, and isolation of system for background noise minimization, which will lead to better accuracy.
2) minimization, which will lead to better accuracy.

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