



Ain Shams University
Faculty of Engineering
Design and Production Engineering Department

Simulation of Sound Propagation through Ducts

By

Sara Mohamed Abd Elmotagally Elsaadany
B.Sc. Mechanical Design and Production Engineering

Submitted in Partial fulfillment of the requirements of the degree
of Master of Science in Mechanical Engineering

Supervised by:

**Associate Prof. Ahmed
Hussein**

Design and production
Engineering Department
Faculty of Engineering
Ain Shams University

Tamer Elnady PH.D

Design and production
Engineering Department
Faculty of Engineering
Ain Shams University

2009

Declaration

The contents of this work are the result of original research and have not been submitted for a similar or higher degree to any other university or institution.

This thesis is the result of my own work and all sources used in it have been furthermore acknowledged.

The work included in this thesis was carried out, at the Sound and Vibration Laboratory (SVLab), Design and Production Engineering Department, Faculty of Engineering, Ain Shams University.

Signature

Sara Mohamed Elsaadany

Acknowledgement

If I'm here now to show my gratitude to the ones had contributed in the process of writing this thesis, I will present a very long list. But, the one first to be thanked is my late mother. Before I was myself she made me, with love patience, discipline and tears, then bit by bit stepped back to set me free. I owe my every past present and future success to her who honestly did her best for my good. My father, for me he is my closest friend who is sharing everything with me, giving me all his trust and growing my self confidence.

Now it is my honor to express my deepest gratefulness and appreciation to Dr. Ahmed Hussein, my supervisor, for always being an ideal model for the engineer in front of my eyes. I can't really count how many things I had learned from him on the scientific, engineering and personal level.

Three years ago, an extremely smart character had joined my life to be me my manager, supervisor and elder brother, Dr. Tamer Elnady. He is the first one who introduced me to the field of acoustics. My thankfulness to him is because he had never saved his energy or time in helping me. He patiently, happily and unconditionally guided and supported me all over the process of working in and writing this thesis.

It is my pleasure to acknowledge and thank the best colleague ever, Eng. Osama Saeed for offering all what he has of time, knowledge and energy to help me. He also has a great help in all the measurements set up.

Also I would like to thank all my teachers and professors who taught me all over my life.

Many thanks to Dr. Wael Akl and Dr. Mohamed Elsamanody for offering me valuable recommendations and answers to every question I had asked them.

It can't be to forget my friends, specially Sara Serag, Sara Salem, Caroline Atef, Noha Yasseen, and Mohamed Abdel Ghany who always give me good time, helping me to restore my energy and honestly wishing me best of all.

Last but not least, I would like to give a bundle of thanks to every member of the Sound and Vibration Laboratory staff, for their continuous supply of support to me.

All words of thanks to Allah Who let me have all these wonderful people there for me.

Committee

The undersigned certify that they have read and recommended to the Faculty of Engineering, Ain Shams University the acceptance of the thesis entitled “*On the Simulation of Sound Propagation through Ducts*” , submitted by Sara Mohamed Elsaadany, in partial fulfillment of the requirements of the degree of masters of science in Mechanical Engineering.

Signature

1. Prof. Dr. Mohammed Taha Hedaya

Professor of Mechanics of Machines
Design & Production Engineering Department
Faculty of Engineering
Ain Shams University, Egypt.

2. Prof. Dr. Mats Åbom

Professor of acoustics
Aeronautical and Vehicle Engineering Department
KTH (Royal Institute of Technology), Sweden.

2. Associate Prof. Dr. Ahmed Mohammed Hussein

Associate Professor of Machine Design
Design & Production Engineering Department
Faculty of Engineering
Ain Shams University, Egypt.

Foreword

Sound propagation in duct systems is an important field. Mainly when trying to prevent the sound propagation to reach openings. To control such a problem during the engineering phase, computational methods should become available, which can predict the behavior of sound propagation through the entire system and effect of the noise on the environment.

The aim of this work is to develop computational tools in order to achieve better description of sound propagation through fluid conveying ducts required for engineering purposes.

These computational tools will handle untouched issues in the field of sound propagation in duct systems.

The work in this research is categorized into two categories.

The first category includes the computation of flow distribution through different paths in order to correctly estimate the change in the impedance of the network elements and to model the convective effects.

While the second category includes

- 1- Studying the gas properties variation with different conditions.
- 2- Calculation of the acoustic pressure outside the system.
- 3- Adding active standardized acoustic sources to the system such as
 - Saw tooth waves
 - Rectangular waves
- 4- Finding an algorithm to automatically generate multi-port elements based on the segmentation approach.
- 5- Play time domain signal of a pressure calculated at a certain node using the computer sound card. This time domain signal is constructed using the inverse Fourier Transform of the frequency spectrum.

List of Figures

Figure	Description
2.1	A two port element.
2.2	Circuit representation of a 1-port assuming a constant pressure source. p^n is the total pressure in node n .
2.3	Moody chart.
2.4	Pipe element.
2.5	Diverging horn.
2.6	Converging horn.
2.7	Horn element.
2.8	Catalytic converter element.
2.9	Diesel particulate filter element.
2.10	Lined duct element.
2.11	Area contraction element.
2.12	Area expansion element.
2.13	Expansion chamber element.
2.14	Area constriction element.
2.15	Perforate element.
2.16	User defined two port element.
2.17	Free space element.
2.18	Baffle element.

- 3.1 The pipe fourpoles.
- 3.2 Setup of two-source method.
- 3.3 Schematic for the test object connected between two pipes.
- 3.4 5" Pipe drawing.
- 3.5 The pipe assembly with the loudspeakers and microphones mounted on it.
- 3.6 SVLab Test Rig.
- 3.7 Schematic for SVLab TL Measuring System.
- 3.8 Schematic for SVLab Pressure Drop Measuring System.
- 3.9 Four Inches Expansion Chamber measured at SVLab.
- 3.10 Through Flow Muffler with One Perforated Pipe.
- 3.11 Muffler with Perforated Plate Filled.
- 3.12 Plug Flow Muffler with One Perforated Pipe.
- 3.13 Two Plugs Flow Muffler with One Perforated Pipe..
- 3.14 Eccentric Muffler with Two Perforated Pipes of 4.8% and 5.4% Porosity.
- 3.15 Eccentric Muffler with Two Perforated Pipes of 10%.
- 3.16 Eccentric muffler with two plugs.
- 3.17 Eccentric muffler with one plug.
- 3.18 The Diesel Paeticulate Filter.
- 3.19 The After Treatment Device (ATD).
- 4.1 Expansion Chamber.

4.2	Simulation network for expansion chamber.
4.3	Results for case 1.
4.4	Results for case 2.
4.5	First Configuration of the Through Flow Muffler with One Perforated Pipe
4.6	Simulation network for the first configuration of the through flow muffler with one perforated pipe.
4.7	Results for case3.
4.8	Results for case 4.
4.9	Results for case 5.
4.10	Results for case 6.
4.11	Results for case 7.
4.12	Muffler with perforated plate.
4.13	Simulation network for muffler with perforated plate in direct flow direction.
4.14	TL results for case 8 at no flow.
4.15	Results for case 9.
4.16	Simulation network for muffler with perforated plate in reverse flow direction.
4.17	Results for case 10.
4.18	Results for case 11.
4.19	Results for case 12.
4.20	

- 4.21 Simulation network for plug flow muffler with one perforated pipe.
- 4.22 Results for case 13.
- 4.23 Results for case 14.
- 4.24 Two Plugs Flow Muffler with One Perforated Pipe.
- 4.25 Simulation network for two plugs flow muffler with one perforated pipe.
- 4.26 Results for case 15.
- 4.27 Results for case 16.
- 4.28 Eccentric muffler with two perforated pipes of 4.8% and 5.4% porosity.
- 4.29 Simulation network for Eccentric muffler with two perforated pipes of 4.8% and 5.4% porosity.
- 4.30 Results for case 17.
- 4.31 Eccentric Muffler with Two Perforated Pipes of 10% Porosity.
- 4.32 Simulation network for eccentric muffler with two perforated pipes of 10% porosity.
- 4.33 Results for case 18.
- 4.34 Eccentric muffler with two plugs.
- 4.35 Simulation network for Eccentric muffler with two plugs.
- 4.36 Results for case 19.
- 4.37 Eccentric muffler with one plug.
- 4.38 Simulation network for Eccentric muffler with one plug.

- 4.39 Results for case 20.
- 4.40 The DPF unit.
- 4.41 Simulation network for the DPF.
- 4.42 Results for case 21.
- 4.43 The after treatment device (ATD).
- 4.44 Simulation network for the ATD.
- 4.45 Results for case 22.
- A-1 Define Gas Data Window from SIDLAB.
- B-1 The position of the receiver with respect to the system outlet.
- B-2 Define Receiver Position Window from SIDLAB.
- C-1 Rectangular wave.
- C-2 Rectangular waveform in the time domain.
- C-3 Rectangular waveform in the frequency domain.
- C-4 Sawtooth waveform in the time domain.
- C-5 Sawtooth waveform in the frequency domain.
- D-1 The Location of the perforate elements. Note: A perforate element is put at the beginning and end. From the figure, it follows that $\Delta x = L / (N-1)$ where N is the number of perforate elements.
- E-1 The original frequency vector.
- E-2 The new frequency vec
- E-3 The new amplitudes vector.

List of Symbols

Symbol	Description
p	Acoustic pressure (Pa).
q	Particle Volume velocity (m/s)
P_s	Static Pressure (Pa)
P	Stagnation Pressure (Pa)
h_e	Head losses (m)
ρ	Density (kg/m^3)
g	Gravitational acceleration (m^2/s)
v	Velocity (m/s)
R_f	Flow Resistance (kg/s^2)
k_e	Loss coefficient
L	Length (m)
D	Diameter (m)
f	Friction factor
A	Area (m^2)
Re	Reynold's number
μ	Dynamic viscosity (Ns/m^2)
θ	Cone angle (deg)
H	Height (m)
n_c	Number of cells per square inch
σ_s	Permeability (m^2)
C_D	Orifice discharge coefficient
M	Mach number
σ	Perforate porosity
T	Transfer matrix
z	Height above the datum (m)
τ	Shear stress on the pipe wall N/m^2
Φ	Specific flow resistance per unit thickness kg/m.s^2
aug	Augmentation factor for catalytic converter
h	Thickness (m)
TL	Transmission loss (dB)
NR	Noise reduction (dB)
IL	Insertion loss (dB)
K	Wave number
f	Frequency (Hz)
c	Speed of sound (m/s)
λ	Wave length (m)
ω	Angular velocity (rad/s)

Table of Contents

1. Introduction.....	1
2. Calculation of Flow Distribution and Pressure Drop.....	9
2.1. Two Port Theory.....	9
2.2. The Proposed Calculation Approach.....	10
2.2.1. Description of two-port elements.....	10
2.2.2. Derivation of the transfer matrix of a two port element.....	11
2.2.3 Description of one-ports.....	13
2.2.4. Solution Scheme for Determination of Flow Distribution.....	16
2.2.5. Determination of flow Resistances of Two Port Elements.....	17
2.2.5.1. Pipe.....	17
2.2.5.2. Horn.....	21
2.2.5.3 Catalytic Converter.....	24
2.2.5.4. Diesel Particulate Filter.....	26
2.2.5.5. Lined Duct.....	28
2.2.5.6. Area Expansion and Area Contraction.....	29
2.2.5.7. Expansion Chamber.....	31
2.2.5.8. Area Constriction.....	31
2.2.5.9. Lumped Element.....	32
2.2.5.10. Perforate.....	33
2.2.5.11. User Defined.....	34
2.2.6. Determination of flow Resistances of Two Port Elements.....	35
2.2.6.1. Reflection Free.....	36
2.2.6.2. Free Space.....	36
2.2.6.3. Baffle.....	36
2.2.6.4. Constant.....	37
2.2.6.5. User Defined.....	37
2.2.7. Proposed Flow Algorithm Flow-chart.....	38
3. Experimental Work	41
3.1 Measurement Methodology.....	42
3.2. Description of Test Rig and Measurement Systems.....	45
3.3. Description of Measured Test Objects.....	51
3.3.1. Expansion Chamber.....	52

3.3.2. Through Flow Muffler with One Perforated Pipe..	53
3.3.2.1 First Form of Through Flow Muffler with One Perforated Pipe.....	53
3.3.2.2 Second Form of Through Flow Muffler with One Perforated Pipe Filled With Absorbing Material	53
3.3.3 Muffler with Perforated Plate Filled with Absorbing Material.....	54
3.3.4. Plug Flow Muffler with One Perforated Pipe.....	54
3.3.5. Two Plugs Flow Muffler with One Perforated Pipe	55
3.3.6 Eccentric Muffler with Two Perforated Pipes.....	55
3.3.6.1 Eccentric Muffler with Two Perforated Pipes of 4.8%and 5.4% Porosity.....	55
3.3.6.2 Eccentric Muffler with Two Perforated Pipes of 10% Porosity.....	56
3.3.7 Eccentric Muffler with Plugs.....	56
3.3.8. Diesel Particulate Filter (DPF).....	57
3.3.9. After Treatment Device (ATD).....	58
4. Correlation between Proposed Simulation and Experimental Results.....	61
4.1. Expansion Chamber.....	61
4.1.1. Case 1:Four Inches Expansion Chamber.....	63
4.1.2. Case 2: Five Inches Expansion Chamber.....	65
4.2. Through Flow Muffler with One Perforated Pipe.....	67
4.2.1. Case 3: Through Flow Muffler with One Perforated Pipe of 12% Porosity.....	68
4.2.2. Case 4: Through Flow Muffler with One Perforated Pipe of 5.5% Porosity.....	71
4.2.3. Through Flow Muffler with One Perforated Pipe of 28% Porosity.....	73
4.2.3.1. Case 5: Through Flow Muffler with One Perforated Pipe of 28% Porosity with Empty Chamber.....	74
4.2.3.2. Case 6: Through Flow Muffler with One Perforated Pipe of 28% Porosity Filled with Absorbing Material (Powertex $R=4000\text{Pa.s/m}^2$)	76
4.2.3.3. Case 7: Through Flow Muffler with One Perforated Pipe of 28% Porosity Filled with Absorbing Material (Powertex $R=7000\text{Pa.s/m}^2$).....	78
4.3. Muffler with Perforated Plate Filled with Absorbing Material.....	80

4.3.1. Muffler with Perforated Plate Tested in Direct Flow Direction.....	80
4.3.1.1. Case 8:Muffler with Perforated Plate without Absorbing Material Tested in Direct Flow Direction	82
4.3.1.2. Case 9: Muffler with Perforated Plate Filled with absorbing material (Powertex R=4000Pa.s/m ²) Tested in Direct Flow Direction.....	83
4.3.2. Muffler with Perforated Plate Tested in Reverse Flow Direction.....	85
4.3.2.1. Case 10: Muffler with Perforated Plate Filled without Absorbing Material Tested in Reverse Flow Direction.....	86
4.3.2.2. Case 11: Muffler with Perforated Plate Filled with Absorbing Material (Powertex R=4000Pa.s/m ²) Tested in Reverse Flow Direction.....	87
4.3.2.3. Case 12: Muffler with Perforated Plate Filled with Absorbing Material (Powertex R=5500Pa.s/m ²) Tested in Reverse Flow Direction.....	89
4.4. Plug Flow Muffler with One Perforated Pipe.....	91
4.4.1. Case 13: Plug Flow Muffler with One Perforated Pipe of Porosity 12%.....	93
4.4.2. Case 14: Plug Flow Muffler with One Perforated Pipe of Porosity 5.5%.....	95
4.5. Two Plugs Flow Muffler with One Perforated Pipe.....	97
4.5.1. Case 15: Two Plugs Flow Muffler with One Perforated Pipe of 14% Porosity.....	99
4.5.1. Case16: Two Plugs Flow Muffler with One Perforated Pipe of 28% Porosity.....	102
4.6. Eccentric Muffler with Two Perforated Pipes.....	105
4.6.1. Case 17: Eccentric Muffler with Two Perforated Pipes of 4.8%and 5.4% Porosity.....	105
4.6.2. Case 18: Eccentric Muffler with Two Perforated Pipes of 10% Porosity.....	108
4.7. Eccentric Muffler with Plugs.....	113
4.7.1. Case 19: Eccentric Muffler with Two Plugs.....	113
4.7.2. Case 20: Eccentric Muffler with One Plug.....	117
4.8. Case 21: Diesel Particulate Filter (DPF).....	123
4.9. Case 22: After Treatment Device (ATD).....	127
5. Discussion Summary and Conclusion.....	131

Appendices.....	
Appendix A: Studying Gas Properties Variation with Different Condition.....	135
Appendix B: Calculation of the Acoustic Pressure outside the System	139
Appendix C: Adding Active Sources to the System.....	142
Appendix D: Automatic Generation of Multi-Ports Elements.....	146
Appendix E: Listening the Sound Pressure at the System Nodes.....	156
Appendix F: Microphones Calibration Charts.....	161
Appendix G: Information about the Tested DPF Unit.....	164
References.....	165