University of Huddersfield Repository

Ngu, Jude T.A.

The effects of turbulence on organ sound quality and its minimisation in blowing systems

Original Citation


This version is available at http://eprints.hud.ac.uk/id/eprint/6909/

The University Repository is a digital collection of the research output of the University, available on Open Access. Copyright and Moral Rights for the items on this site are retained by the individual author and/or other copyright owners. Users may access full items free of charge; copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational or not-for-profit purposes without prior permission or charge, provided:

- The authors, title and full bibliographic details is credited in any copy;
- A hyperlink and/or URL is included for the original metadata page; and
- The content is not changed in any way.

For more information, including our policy and submission procedure, please contact the Repository Team at: E.mailbox@hud.ac.uk.

http://eprints.hud.ac.uk/
The Effects of Turbulence on Organ Sound Quality and its Minimisation in Blowing Systems

Jude T.A. NGU
Division of Mechanical Engineering
School of Engineering
University of Huddersfield

April 1995
The Effects of Turbulence on Organ Sound Quality and its Minimisation in Blowing Systems

Jude Thaddeus Anye NGU
B.Sc (Essex). M.Sc.(Lond) AMIEE. MIEEE

Thesis Submitted to the University of Huddersfield in Partial Fulfilment of the Requirements for the degree of Doctor of Philosophy

April 1995

Director of Studies
Prof. H. V. Rao. (School of Engineering.)

Supervisors
Mr. Keith Jarvis (School of Music and Humanities, University Organist)
Dr. Keith Sherwin (School of Engineering)

Advisers
Dr. Paul F. Arthur (Assistant Principal)
Prof. George Pratt (School of Music and Humanities)

The University of Huddersfield in Collaboration with:

Wood of Huddersfield,
Organ Builders, St. Andrews Rd, Huddersfield.
(Directors: Mr. Philip Wood and Mr. David Wood)
Dedication

To my parents;

Ambrose Ngang Ngu
&
Theresia Mbunue Ngu
I have always wanted my work to have the lightness and joy of springtime which never lets anyone suspects the labour it has cost.

_Henri Matisse_

The improvement of understanding is for two ends: first our own increase of knowledge; secondly to enable us to deliver that knowledge to others.

约翰·洛克

It is not by discoveries only and the registration of them by learned societies that science is advanced. The true seat of science is not the volumes of transactions but in the living mind.

匿名者
This research project could not have been realised without the help and support of many people and institutions. It is only fair that I take this opportunity to express my gratitude to all of them.

My profound gratitude goes to the University of Huddersfield for providing me with a studentship to undertake this research. The directors of Wood of Huddersfield (industrial collaborators in this project), Philip Wood and David Wood provided me with a lot of assistance for which I am also deeply grateful. Thanks also to Mark Venning of Harrison & Harrison organ builders, Durham, for all his help.

I am delighted to have had my studies directed by Professor Vasu Rao (School of Engineering) and supervised by Keith Jarvis (School of Music and Humanities) and Dr. Keith Sherwin (School of Engineering). Their constructive criticism and guidance throughout this work has been immeasurable and extremely valuable. I would also like to thank Professor George Pratt who also provided useful advice and assistance during this project. I also owe some gratitude to Dr. Bill Weston, Deputy Dean, School of Engineering, who was immensely helpful throughout this research.

My gratitude also goes to Dr. Paul Arthur, Assistant Principal, who provided us with a lot of support throughout this project.

The entire staff of the research office were very helpful. In particular, I wish to thank Mrs. Rosalind Watt, Assistant Registrar, Research and Validation for all her support. Ros, Muyaka (Thanks in my language, Mankon)! You have been very marvelous.

May I also thank the technicians in the School of Engineering for all their assistance; in particular, Peter Norman for all his help with the building and setting up of my test rigs, Graham Butler and Adam Isherwood for sorting out the SUN computers when the machines threatened to hold up my work. My gratitude also goes to Mark Bromwich, the Electro-Acoustic Studio Manager for all his help.

I would also like to express my gratitude to the security staff and caretakers of the engineering block and Z-block for putting up with my irregular working hours. You all have been magnificent.

Thanks also goes to my colleagues in the research students office (Z2/44): Steve Kendal, David Palmer, Michael Fish, Nihat Yildrim and Craig Edwards for the useful discussions we had. Those discussions helped my Electronic Engineering tuned mind come to terms with some of the complexities of Mechanical Engineering. I would also like to thank the secretaries in the School of Engineering, Mrs. Laurie Hampshire, Mrs. Jane Godfrey and Mrs. Jill Healey for all their help and for putting up with my incessant demands on their time.

Finally, I will like to thank my family and friends for their invaluable support throughout this research. My parents, Ambrose Ngang Ngu and Theresia Mbunue Ngu as well as Fru Ngu, Folong Ngu, Atanga Ngu, Chewfung Ngu, Aghanwi Ngu, Manka Ngu, Mambo Nyamnjoh, Francis Nyamnjoh, Anye-Nkwenti Nyamnjoh, Miss Mum, Andrew Tembon, Mercy Tembon, N N Susungi, Mme P Susungi, Agbor Nhu, Donna Francis, Rahan Shaheen, Ade Angwafo III, Sule Nfomi, Erica Charles, Saah Lamango and all others who for want of space have not been mentioned here.

I hope that in finishing this work, I have done all of you, who helped me in any way, very proud.
ABSTRACT

This research sets out to study the effects of turbulence on organ sound and examine ways of minimizing it in blowing systems.

The efficacy of application of statistical and spectral techniques for a quantitative analysis of the effects of turbulence on the organ sound has been established.

The sound generated for different inlet levels of turbulence intensity were analyzed. The inlet turbulence variation was achieved by mixing in different proportions, the wind generated by a centrifugal fan which has high levels of turbulence and turbulence attenuated wind. The latter was obtained by suppressing the levels of turbulence through flow stratification in narrow channels. Turbulence attenuation by flow stratification was used in this research as it could attenuate turbulence for very high Reynolds number (> $10^5$) flows such as encountered in the study.

The effects of turbulence attenuation were evaluated aurally, in a qualitative manner and also analyzed quantitatively. The aural evaluation indicates that changes in the sound with changing levels of turbulence were perceivable. In addition, the lower the turbulence levels, the better the sound quality - the instrument (organ) is said to have a better "degree of articulation... and expressiveness." Spectral analysis of certain notes with and without turbulence attenuation showed changes to the spectral shape. Ripples in the spectra in the leading and trailing edges of the fundamental were much reduced. The spectra were smoother. The fundamental frequency shifted, on average by 0.3%, up or down, depending on the nicking condition of the pipe. In one note, F#4, the fundamental had two peaks without any turbulence attenuation. One of the peaks vanished when turbulence attenuated wind was used.

A technique was developed for quantitatively evaluating the fundamental from the frequency spectra. The fundamentals were sampled, normalized and moments taken about the central frequency. The 3rd and 4th moments computed gave an indication of the changing skewness and "peakedness" of the note with turbulence. It was noted, from experiments conducted on a test rig, that the notes got more negatively skewed and peaks more with increasing turbulence attenuation. It was also noted that the notes underwent a non-monotonical increase in asymmetry with falling levels of turbulence. There were similar increments in the "peakedness" of the pipe fundamental amplitude with decreasing turbulence.

An electrical analogous circuit of the organ flue pipe for turbulence studies was developed. A circuit model with linear components was simulated and tested. It was found that most of the circuit component parameters were dependent on the geometric dimensions of the pipe, especially the pipe length. Calculations and a simulation of the circuit using HSPICE with parameters determined using the effective length of the pipe gave resonant frequencies much less than those obtained from acoustic experiments. The concept of an active length, $L_a$, which works out to be a third of the effective length, $L_e$, was introduced. Calculations and simulations using $L_a$ gave more accurate results. A hardware implementation of the circuit developed was also done in order to study the effects of turbulence.

The statistical analysis and electrical analysis studies undertaken in the current work may find application in the design of computer organs and other areas were turbulence in flow plays a significant role.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Title</th>
<th>i</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dedication</td>
<td>iii</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>v</td>
</tr>
<tr>
<td>Abstract</td>
<td>vi</td>
</tr>
<tr>
<td>Table Of Contents</td>
<td>vii</td>
</tr>
<tr>
<td>List Of Figures</td>
<td>xiii</td>
</tr>
<tr>
<td>List Of Tables</td>
<td>xvi</td>
</tr>
<tr>
<td>List Of Symbols</td>
<td>xvii</td>
</tr>
<tr>
<td><strong>CHAPTER ONE</strong></td>
<td></td>
</tr>
<tr>
<td><strong>INTRODUCTION</strong></td>
<td></td>
</tr>
<tr>
<td>1.1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Previous Work</td>
<td>3</td>
</tr>
<tr>
<td>1.3 An overview of the Organ and Organ Pipe</td>
<td>4</td>
</tr>
<tr>
<td>1.4 Thesis outline</td>
<td>8</td>
</tr>
<tr>
<td><strong>CHAPTER TWO</strong></td>
<td></td>
</tr>
<tr>
<td><strong>A REVIEW OF ORGAN BLOWING MECHANISMS</strong></td>
<td></td>
</tr>
<tr>
<td>2.1 Manaul Blowers</td>
<td>11</td>
</tr>
<tr>
<td>2.2 Hydraulic Blower</td>
<td>11</td>
</tr>
<tr>
<td>2.3 The Gas Engine</td>
<td>13</td>
</tr>
<tr>
<td>2.4 The Centrifugal Fan as an Organ Blowing Machine</td>
<td>14</td>
</tr>
<tr>
<td>2.4.1 The Kinetic Blower</td>
<td>14</td>
</tr>
</tbody>
</table>

vii
| 2.4.2 | The Centrifugal Blower | 15 |
| 2.4.3 | Advantages of the Centrifugal and Kinetic Blowers | 16 |
| 2.4.4 | The Disadvantages of the Centrifugal and Kinetic Blowers. | 16 |
| 2.5 | Surmounting the Defects of the Centrifugal Machine | 18 |
| 2.5.1 | Modifications to the Impeller Blade Geometry | 18 |

**CHAPTER 3**

TURBULENCE SUPRESSION AND ATTENUATION

3.1 Principles of Turbulence Attenuation and Suppression

3.1.1 Dissipative Reversion.

3.1.2 Richardson Type Reversion (Dissipation via Stabilized Stratified Flows)

3.1.3 Reversion by Domination.

3.2 Some Techniques used to realise reversion.

3.2.1 Curved Flows

3.2.2 Turbulence Attenuation via Spanwise Axis rotation of the Flow Channel

3.2.3 Channel Enlargement

3.2.4 Turbulence Reversion using Helically Coiled Pipes

3.2.5 Turbulence attenuation by flow stratification

3.2.6 Choice of turbulence attenuation or suppression technique

**CHAPTER FOUR**

EFFECTS OF TURBULENCE ATTENUATION

4.1 The Turbulence Attenuator (Filter)

4.2 Evaluation of the Turbulence Attenuator

4.2.1 Choice of Flow Measurement Equipment

4.3 Fluid Dynamic Evaluation of the Turbulence Attenuator

4.3.1 Spectral measurement of turbulence

4.3.2 Turbulence in the time domain
4.4 Relationship Between Attenuator Honeycomb Length $L_w$ and Cutoff Frequency of Turbulence ........................................ 44
4.5 Acoustic Evaluation of the Turbulence Attenuator. .......................... 47
  4.5.1 A Qualitative Evaluation ...................................................... 47
  4.5.2 A Quantitative Evaluation ..................................................... 56
4.6 Use of Centrifugal Fan at off Optimum Design Condition as means of Minimizing Turbulence .................................................. 57

CHAPTER 5 ................................................................................................. 60

AN EVALUATION OF THE EFFECTS OF TURBULENCE ATTENUATION. .......... 60
5.1 Introduction .......................................................................................... 60
5.2 Evaluation of data from test rig ............................................................. 62
  5.2.1 Test rig design. ............................................................................. 62
  5.2.1.1 The test rig. .............................................................................. 64
5.3 An aural assessment of the tones from test rig .......................................... 66
  5.3.1. An assessment via individual remarks ........................................... 66
  5.3.2. An assessment via questionnaire .................................................. 68
5.4 An aural evaluation of St. Paul’s Data ..................................................... 71
5.5 Quantitative Evaluation of Pipe Data ..................................................... 72
  5.5.1 Evaluation of moment of data from test rig .................................... 73
    5.5.1.1 Third moments of test rig data ................................................. 73
    5.5.1.2 Fourth moments of test rig data .............................................. 74
  5.2 Evaluation of moments of data from St. Paul’s ..................................... 75
    5.5.2.1 Moments of St Paul’s Data .................................................... 75
5.6 Effects of changing flow conditions on frequency .................................... 77
  5.6.1 Frequency variations and Turbulence in St Paul’s Organ ..................... 78
5.7 Comparison between the Human Blower and Centrifugal Blower. ............. 82
  5.7.1 Third moments ............................................................................ 83
  5.7.2 Fourth moments ........................................................................... 84
5.7.3 Frequency variations

CHAPTER SIX

ON AN ELECTRICAL ANALOGOUS CIRCUIT OF THE ORGAN PIPE FOR TURBULENCE STUDIES

6.1 Electrical Analogues of Mechanical Elements.
   6.1.1 Impedance
   6.1.2 Capacitance
   6.1.3 Inductance
   6.2.1 The Pipe Input Impedance
   6.2.2 Pipe Mouth Impedance
   6.2.3 Pipe Resonator Impedance
   6.2.4 Pipe Termination Impedance

6.5 Rules of Arrangement of Circuit Components
6.5 Calculation of Circuit Impedances
6.6 Computer Simulation of Pipe Analogous Circuits
   6.6.1 Circuit Simulation Results
   6.6.2. Circuit Simulation using the Pipe Active Length.
   6.6.3 The Study of Turbulence Effects by Electrical Circuit Simulation.
   6.6.4. Evaluating Pipe Analogous Circuits by Experiment.
   6.6.5 Non-linearity of Circuit Components of Organ Pipe Analogous Circuits.

CHAPTER 7

OTHER APPLICATIONS AND PROPOSALS FOR FURTHER RESEARCH

7.1 Other Applications of this Research 129
   7.1.1 Resonance Effects in Moving Vehicles 129
   7.1.2 Studying Pulsations in Gas Plants 130
   7.1.3 Other Applications in Organs 131
# Table of Contents

7.2 Proposals for Further Research  

CHAPTER 8  

CONCLUSIONS  

APPENDICES  

APPENDICES  

APPENDIX 1  
Some notes on the St Paul's organ  

APPENDIX 2  

APPENDIX 3  

A3 A Theoretical Overview of Turbulence  

A3.1 Turbulence: Some Definitions  

A3.2 The Statistical Nature of Turbulence  

A3.2.1 Assumptions made on the statistical nature of turbulence  

A3.3 Spectral Analysis of Turbulence  

A3.3.1 Principles of Correlation Techniques in the Spectral Analysis of Turbulence  

APPENDIX 3B  

A-3.4 Derivation of the Covariance for two Random Continuous Data  

APPENDIX 4  

A-4 Calculations for the Turbulence Suppressor Built for St. Paul's  

Determination of Re before honeycomb passage:  

Determination of Re,p within honeycomb passage  

APPENDIX 5  

A-5 Procedure for Checking the Frequency Response of the Constant Temperature Anemometer(CTA)  

APPENDIX 6  

A-6 Questionaire on Research on the Effects of Turbulence on Organ Pipe Sound.
APPENDIX 7
A7.2 On (statistical) moments
   A7.2.1 On the fourth moment
   A7.2.2 On the third moment
A7.3 Numerical analysis of pipe fundamentals.
A7.4 Application of principles of moments to evaluation of experimental data
APPENDIX 8a
A-8a Flow chart of MINITAB programme used to calculate moments
APPENDIX 8b
A-8b Sampled Data from St Paul's (an example)
APPENDIX 9
A-9 Example of Test Rig Sampled Data
APPENDIX 10
A-10 Flow Chart of Maple Program used to determine pipe circuit parameters.
APPENDIX 11
APPENDIX 12
A-11 Manipulating the Wirelisting to Introduce a Turbulence(noise) input

REFERENCES
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig 1.1</td>
<td>Anatomy of the Organ Flue Pipe5</td>
</tr>
<tr>
<td>Fig 1.2</td>
<td>Basic block diagram of the organ6</td>
</tr>
<tr>
<td>Fig 1.3</td>
<td>Schematic to illustrate the sounding mechanism of organ pipe</td>
</tr>
<tr>
<td>Fig 2.1</td>
<td>Sketch of four persons handblowing an organ.</td>
</tr>
<tr>
<td>Fig 2.2</td>
<td>Two persons blowing an organ with their feet -Halberstadt Cathedral Organ-16th Century</td>
</tr>
<tr>
<td>Fig 2.3</td>
<td>An example of a hydraulic machinery used for organ blowing</td>
</tr>
<tr>
<td>Fig 3.1</td>
<td>Schematic diagram to demonstrate reversion by means of curved flows</td>
</tr>
<tr>
<td>Fig 3.2</td>
<td>Reversion due to channel enlargement</td>
</tr>
<tr>
<td>Fig 3.3</td>
<td>Turbulence reversion in flow through helically coiled pipes.</td>
</tr>
<tr>
<td>Fig 3.4</td>
<td>Section of schematic for turbulence attenuation by stratified flow</td>
</tr>
<tr>
<td>Fig 4.0</td>
<td>Turbulence attenuator built for the St. Paul’s Organ, Univ. of Huddersfield. 34</td>
</tr>
<tr>
<td>Fig 4.1</td>
<td>Experimental Setup for the Evaluation of the Turbulence attenuator</td>
</tr>
<tr>
<td>Fig 4.2</td>
<td>Spectrograph of still air</td>
</tr>
<tr>
<td>Fig 4.3</td>
<td>Spectrum of wind before attenuator was installed</td>
</tr>
<tr>
<td>Fig 4.4</td>
<td>Spectrum of wind after attenuator was installed</td>
</tr>
<tr>
<td>Fig 4.5</td>
<td>Time domain oscillograph of turbulence signal before filtering</td>
</tr>
<tr>
<td>Fig 4.6</td>
<td>Time domain oscillograph of turbulence signal after filtering</td>
</tr>
<tr>
<td>Fig 4.7</td>
<td>Time domain oscillograph (zoomed in) of turbulence signal after filtering</td>
</tr>
<tr>
<td>Fig 4.8</td>
<td>An example of a statistical stationary random signal r(t)</td>
</tr>
<tr>
<td>Fig 4.9</td>
<td>Changing cut-off freq. &amp; pressure loss with filter length</td>
</tr>
<tr>
<td>Fig 4.10</td>
<td>Turbulence spectrograph before filtering</td>
</tr>
<tr>
<td>Fig 4.11</td>
<td>Turbulence spectrograph after filtering, $L_w = 250$</td>
</tr>
<tr>
<td>Fig 4.12</td>
<td>Turbulence spectrograph after filtering, $L_w = 300$</td>
</tr>
<tr>
<td>Fig 4.13</td>
<td>Block Diagram of System used for Qualitative Evaluation of attenuator</td>
</tr>
<tr>
<td>Fig 4.14</td>
<td>The F#43 on the 8ft Gedackt stop before turbulence filtering</td>
</tr>
<tr>
<td>Fig 4.15</td>
<td>The F#43 on the 8ft Gedackt stop after turbulence filtering</td>
</tr>
<tr>
<td>Fig 4.16</td>
<td>The C37 on the 8ft Gedackt stop before turbulence filtering</td>
</tr>
<tr>
<td>Fig 4.17</td>
<td>The C37 on the 8ft Gedackt stop after turbulence filtering</td>
</tr>
<tr>
<td>Fig 4.18</td>
<td>The E29 note on the 8ft Gedackt stop before turbulence filtering</td>
</tr>
<tr>
<td>Fig 4.19</td>
<td>The E29 note on the 8ft Gedackt stop after turbulence filtering</td>
</tr>
<tr>
<td>Fig 4.20</td>
<td>The A#23 note on the 2ft Pricipal stop before turbulence filtering</td>
</tr>
<tr>
<td>Fig 4.21</td>
<td>The A#23 note on the 2ft Pricipal stop after turbulence filtering</td>
</tr>
<tr>
<td>Fig 4.22</td>
<td>The C1 note on the 2ft Pricipal stop before turbulence filtering</td>
</tr>
<tr>
<td>Fig 4.23</td>
<td>The C1 note on the 2ft Pricipal stop after turbulence filtering</td>
</tr>
<tr>
<td>Fig 4.24</td>
<td>The F30 note on the Rohrflute 4ft stop before turbulence filtering</td>
</tr>
</tbody>
</table>

---

xiii
Fig. 4.25 The F₃₀ note on the Rohrflute 4ft stop after turbulence filtering 54
Fig. 4.26 The C♯₃₀ note on the Rohrflute 4ft stop before turbulence filtering 55
Fig. 4.27 The C♯₃₀ note on the Rohrflute 4ft stop after turbulence filtering 55
Fig. 4.28 Head, Power & Efficiency vs flow rate for Harisson Centrifugal Blower(before turbulence filter installed) 58
Fig. 4.29 Head, Power & Efficiency vs flow rate for Harisson Centrifugal Blower(after turbulence filter installed) 59
Fig. 5.1 Sketch of experimental rig 63
Fig 5.3 Plots of skewness with increasing laminar flow 74
Fig 5.4 Plots of the fourth moments vs flow for test rig data. 75
Fig. 5.5 Δf vs flow condition 81
Fig. 5.6 Pipe languid with nicking 82
Fig 6.1: Basic Configuration of Organ Pipe 91
Fig 6.2: Block Diagram of Musical Wind Instrument 91
Fig 6.3. Pipe circuit model - development stage 1 101
Fig. 6.4 Pipe circuit model - development stage 1I 102
Fig. 6.5 Pipe circuit model - development stage 1II 103
Fig. 6.6 Pipe circuit model - development stage 1V 103
Fig 6.7 Pipe circuit model - final stage 104
Fig 6.7 Block Diagram of Pipe Resonator 106
Fig 6.8 Response of HSPICE simulation of the equivalent circuit of pipe 1 108
Fig 6.9 Response of HSPICE simulation of the equivalent circuit of pipe 2 109
Fig 6.10 Response of HSPICE simulation of the equivalent circuit of pipe 3 109
Fig 6.11 Response of HSPICE simulation of the equivalent circuit of pipe 4 110
Fig 6.12: Circuit of Noise Generator 111
Fig 6.13 Block Diagram of Circuit Layout 112
Fig 6.14 Block Diagram of Circuit Simulated 113
Fig 6.15 Response of hardware equivalent circuit of pipe 1 (0% Turbulence) 117
Fig 6.16 Response of hardware equivalent circuit of pipe 1 (25% Turbulence) 118
Fig 6.17 Response of hardware equivalent circuit of pipe 1 (50% Turbulence) 118
Fig 6.18 Response of hardware equivalent circuit of pipe 1 (75% Turbulence) 118
Fig 6.19 Response of hardware equivalent circuit of pipe 1 (100% Turbulence) 119
Fig 6.20 Response of hardware equivalent circuit of pipe 2 (0% Turbulence) 119
Fig 6.21 Response of hardware equivalent circuit of pipe 2 (25% Turbulence) 119
Fig 6.22 Response of hardware equivalent circuit of pipe 2 (50% Turbulence) 120
Fig 6.23 Response of hardware equivalent circuit of pipe 2 (75% Turbulence) 120
Fig 6.24 Response of hardware equivalent circuit of pipe 2 (100% Turbulence) 120
Fig 6.25 Response of hardware equivalent circuit of pipe 3 (0% Turbulence) 121
| Fig 6.26 | Response of hardware equivalent circuit of pipe 3 (25% Turbulence) | 121 |
| Fig 6.27 | Response of hardware equivalent circuit of pipe 3 (50% Turbulence) | 121 |
| Fig 6.28 | Response of hardware equivalent circuit of pipe 3 (75% Turbulence) | 122 |
| Fig 6.29 | Response of hardware equivalent circuit of pipe 3 (100% Turbulence) | 122 |
| Fig 6.30 | Response of hardware equivalent circuit of pipe 4 (0% Turbulence) | 122 |
| Fig 6.31 | Response of hardware equivalent circuit of pipe 4 (25% Turbulence) | 123 |
| Fig 6.32 | Response of hardware equivalent circuit of pipe 4 (50% Turbulence) | 123 |
| Fig 6.33 | Response of hardware equivalent circuit of pipe 4 (75% Turbulence) | 123 |
| Fig 6.34 | Response of hardware equivalent circuit of pipe 4 (100% Turbulence) | 124 |
| Fig 6.35 | Electrical Equivalent Circuit of Organ Flue Pipe | 125 |
| Fig 6.36: | Electrical Equivalent Circuit of Organ Pipe in Impedance Blocks | 126 |
| Fig a1: | Overall view of sound board | 138 |
| Fig a2 | An example of a statistical stationary random signal r(t) | 142 |
| Fig a3 | An illustration of a non-stationary random signal r^1(t) | 142 |
| Fig. a4: | Dissection of Suppressor Passage. | 150 |
| Fig. a5: | Setup for measuring CTA frequency response (Scanned from TSI Manual) | 152 |
| Fig a6: | Output trace for probe frequency response test (Scanned from TSI Manual) | 152 |
| Figure a7.1 | Curve shapes for different types of 4th moments. | 154 |
| Fig a7.2 | Distributions illustrating types of 3rd moments | 155 |
| Fig a7.3 | Sampling of frequency data for analysis | 158 |
| Fig a10.1 | Anatomy of the Organ Flue Pipe | 169 |
| Fig a10.2 | Anatomy of the Organ Flue Pipe | 169 |
List of Tables

Cut Off Frequencies & Pressure Drop for Different Attenuator Lengths 44
Turbulence Effects on Note Symmetry, St. Paul's) 69
Turbulence Effects on Physical Sharpness (St. Paul's) 70
Frequency Shift With Change in Turbulence Condition 71
Flow Conditions of Test Rig 75
Audience response to questionnaire 93
Data Table of Skewness with Increasing Laminar Flow 76
Fourth Moments for Different Flow Conditions 77
Measured Frequency Shifts 79
Normalised Frequency Shifts with Changing Flow Conditions 80
Third Moments Human vs Centrifugal Blowing 87
4th Moments - Human vs Centrifugal Blowing 88
Frequency Shifts from Human to Centrifugal Blowing 89
Calculated $f_r$ Based on Pipe Effective Length vs Actual Acoustic Frequencies 105
Circuit Component Values 107
Calculated Simulated and Acoustic Resonant Frequencies of Pipe 108
Flow Conditions 114
Current Output of Signal and Noise Generators 116
Electrical Equivalence of Flow Conditions 116
Calculated, Simulated, Acoustic and Hardware $f_r$ of Pipe Circuits 124

Tables in Appendix

Musical Appreciation of Turbulence Effects 153
Sampled Data from St Paul's (an example) 162
Example of Test Rig Sampled Data 165
Pipe Dimensions 168
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Pipe radius</td>
</tr>
<tr>
<td>a</td>
<td>Channel radius</td>
</tr>
<tr>
<td>A</td>
<td>Area</td>
</tr>
<tr>
<td>A</td>
<td>Amplitude</td>
</tr>
<tr>
<td>A1</td>
<td>Channel arm 1</td>
</tr>
<tr>
<td>A2</td>
<td>Channel arm 2</td>
</tr>
<tr>
<td>A_p</td>
<td>Data point</td>
</tr>
<tr>
<td>BPF</td>
<td>Band pass frequency</td>
</tr>
<tr>
<td>c</td>
<td>Speed of sound</td>
</tr>
<tr>
<td>C_yx</td>
<td>Covariance between signals y and x</td>
</tr>
<tr>
<td>C</td>
<td>Capacitance</td>
</tr>
<tr>
<td>D</td>
<td>Diameter</td>
</tr>
<tr>
<td>DD</td>
<td>Diode</td>
</tr>
<tr>
<td>E[]</td>
<td>Expectation of []</td>
</tr>
<tr>
<td>E(s)</td>
<td>Source Potential, emf, driving voltage</td>
</tr>
<tr>
<td>f</td>
<td>Frequency</td>
</tr>
<tr>
<td>f_c</td>
<td>Central frequency</td>
</tr>
<tr>
<td>f'</td>
<td>Frequency</td>
</tr>
<tr>
<td>F</td>
<td>Frequency</td>
</tr>
<tr>
<td>G_{yy}</td>
<td>One sided auto-spectrum of Y(t)</td>
</tr>
<tr>
<td>I</td>
<td>Current</td>
</tr>
<tr>
<td>ID</td>
<td>Inner diameter</td>
</tr>
<tr>
<td>K</td>
<td>Bulk modulus</td>
</tr>
<tr>
<td>K'</td>
<td>Loss parameter</td>
</tr>
<tr>
<td>K'1</td>
<td>Loss parameter</td>
</tr>
<tr>
<td>L</td>
<td>Inductance</td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
</tr>
<tr>
<td>L_{co}</td>
<td>Honeycomb length</td>
</tr>
<tr>
<td>m</td>
<td>Mass</td>
</tr>
<tr>
<td>M</td>
<td>Inertance</td>
</tr>
<tr>
<td>M</td>
<td>Moment</td>
</tr>
<tr>
<td>M_{k}</td>
<td>K^{th} moment about y</td>
</tr>
<tr>
<td>M_{cs}</td>
<td>Moment coefficient of skewness</td>
</tr>
<tr>
<td>M_{ck}</td>
<td>Moment coefficient of kurtosis</td>
</tr>
<tr>
<td>^1M_{k}</td>
<td>K^{th} moment about the mean</td>
</tr>
<tr>
<td>N_{b}</td>
<td>Number of blades on an impeller</td>
</tr>
<tr>
<td>o/p</td>
<td>output</td>
</tr>
</tbody>
</table>
OD Outer diameter
p Pressure
P Pressure
P1 Pipe 1
P2 Pipe 2
P3 Pipe 3
P4 Pipe 4
Q Volume flow rate
Q Quality factor
Qe Charge
r Radius
R Resistance
Re Reynolds number
RPM Rotations per minute
Ryx Cross correlation between Y(t) and X(t)
S Cross sectional area
Sx Sensor for X(t)
Sy Sensor for Y(t)
Syy Autospectrum of Y(t)
Syx Cross power spectral density between Y(t) and X(t)
u' turbulence intensity
U Flow velocity
Up Mean flow in honeycomb
V Speed
V Voltage
V1 Valve 1
V2 Valve 2
V3 Valve 3
X Random variable
X' Velocity
X(t) Arbitrary signal
Y(t) Arbitrary signal
Z Impedance

Greek Alphabet

β Blockage ratio
µ Viscosity
\[ \mu \quad \text{Moment} \]
\[ \mu \quad \text{Mean} \]
\[ \rho \quad \text{Density} \]
\[ \theta \quad \text{Half angle of deviation} \]
\[ \psi \quad \text{Some origin} \]
\[ \Delta f \quad \text{Normalised frequency shift} \]
\[ \Delta V \quad \text{Volume displacement} \]
\[ \Delta p \quad \text{Pressure drop} \]
\[ \tau \quad \text{Time delay} \]
\[ \tau \quad \text{Pulse width} \]
\[ \infty \quad \text{Infinity} \]

**Subscripts**

\[ a \quad \text{Active} \]
\[ cp \quad \text{Pipe capacitance} \]
\[ C \quad \text{Capacitance} \]
\[ d \quad \text{Downstream} \]
\[ e \quad \text{Effective} \]
\[ eff \quad \text{Effective} \]
\[ in \quad \text{Input} \]
\[ j \quad \text{Jet} \]
\[ Lp \quad \text{Pipe inductance} \]
\[ L \quad \text{Inductance} \]
\[ m \quad \text{Pipe mouth} \]
\[ \max \quad \text{Maximum} \]
\[ \min \quad \text{Minimum} \]
\[ n \quad \text{Normalised} \]
\[ n \quad \text{Resonant mode} \]
\[ p \quad \text{Pipe} \]
\[ T \quad \text{Termination} \]
\[ u \quad \text{Upstream} \]
\[ x \quad \text{Signal } X(t) \]
\[ y \quad \text{Signal } Y(t) \]
\[ 100T \quad 100\% \text{ turbulence} \]
CHAPTER ONE

INTRODUCTION

1.1 Introduction

The musical organ has been in existence for about 2000 years.\(^{34}\) It would be expected that enough work would have been done to explain the acoustics, fluid dynamics and aero-acoustics of the instrument by now. This does not seem to be the case. There is still a lot of work to be done. In fact, "there are still many problems in understanding details of the mechanism by which the sound is produced!";\(^{34}\) these "details" are not yet "well established"\(^{16}\). The amount of research being carried out around the world - Australia, Japan, Hungary, Germany, Holland, France and USA - seems to indicate that a lot of knowledge still has to be squeezed out from this domain not only to shed light on the behaviour of organ pipes and similar wind instruments but also the behaviour of other aero-acoustic mechanisms that are similar to those occurring in organ pipes.

Some research has also been done to throw more light on the musical acoustics of the organ pipe.\(^{3}\)\(^{25}\)\(^{42}\)\(^{49}\) In Hungary, some studies were conducted to study the build up of sound in the organ.\(^{3}\) Some researchers have also studied the evolution of the timbre with changing tessitura\(^{25}\). Others have conducted research to understand the interaction between the mouths of resonating pipes placed on the same soundboard.\(^{49}\)

Several researchers have invested a lot of efforts to studying the jet stream from the flue and its interaction with the resonant modes of the pipe, see for example references 10, 29-36. Different aspects of this flow interaction have been studied.

Research work on the organ sound production has not been confined to studies on the pipe.

---

1. section of total compass of voiced part of organ in which most tones lie
There has been research undertaken to study the flow in the note channel and wind trunks delivering wind into the organ. These studies did not investigate the effects of turbulence on the pipe sound quality; they were mainly concerned with the effect of pressure pulsations on the pipe sound or reverberation of the bellows.

Caddy and Pollard and others studied the transient sounds and their implications on the steady state resonance of the organ pipe but did not consider turbulence effects. In Spain, Agullo and Martinez have studied the behaviour of pressure waves (not turbulence) within cones similar to the organ pipe foot, but did not look at their subsequent effects on any resonant column that could be attached to such "conical bores".

Studies have also been conducted on the voicing of organ pipes, the end corrections and resonance frequencies of the pipe, flow at the pipe exit during resonance, the quality of the tones as well as relation between pipe resonance and its sound spectra.

Research was carried out on the fluid dynamics of organ pipes not to understand the aesthetics of its musical character, but to extend and apply that knowledge to other applications. Most of this work has been done in France, Holland and USA. Elder has applied some of the findings from his investigations of organ pipe aero-acoustics to study jets generated in moving vehicles and flow noise in research conducted for the US Navy. In Holland and France, considerable research has been conducted on the aero-acoustics of organ pipes and subsequently applied to the analysis of flow excited resonance in gas pipe lines. Studies have also been conducted in the UK on the fluid dynamics of flow excited resonance in ducts using some of the arguments developed in the study of the aero-acoustics of organ pipes.

The main areas of the research on organs are concentrated around the soundboard, pipe jet drive mechanism and the interaction between the jet from the flue and the resonance
modes of the pipes. Very little effort has been invested in studying the wind delivery system of the organ. Studies on organ wind-delivery have mainly been discussion papers on the problems faced, mainly one of unsteady wind and insufficient pressure and an expression of the desire for smooth flowing wind.\textsuperscript{59, 94, 96} Research on wind supply into organs has mainly looked at the pressure fluctuations in the wind.\textsuperscript{39, 77} Rooij\textsuperscript{77} studied the effects of pressure waves in the wind system on pipe sound. Gueritey investigated the effects of pressure waves on the pipe sound when an organ is being played\textsuperscript{39} and showed that there was a discernible shift in the frequency of the fundamental of a pipe. In the investigations carried out to study the effects of pressure waves in the wind-delivery on the pipe sound, it has to be borne in mind that pressure waves are deterministic quantities unlike turbulent fluctuations which are random.

Of all the previous research carried out on the organ, apart from Hirschberg who evaluated the effects of jet (from the pipe flue) turbulence on pipe tones in his paper on the fluid dynamics of speech, no other study was found to have been conducted to study the effects of turbulence from the wind-delivery system on the quality of organ sound. Hirschberg demonstrated that the jet turbulence produces low levels of broad band spectra which are modulated by the pipe modes.

1.2 Previous Work

When the St. Paul's organ\textsuperscript{1} was built, in 1977, the organ blower was placed inside the organ case behind the console (keyboard). Although the fan was placed in an acoustic box, mechanical noise was audible throughout the building. Preliminary tests taken in 1981 suggested that much of the noise was impeller generated. In 1985 the blower was moved to an adjacent cellar. 40 ft (~12 m) of wooden trunking was constructed and installed leading from the blower to the organ. The resiting of the fan improved the sound of the

\textsuperscript{1} Details of the stop list, compass of notes on the organ console and the pipe scale of the St Paul's organ are given in appendix 1
instrument, reducing the shrillness of the instrument, and improving the tonal blend of the organ stops. An added benefit was the improvement in the touch of manual III (swell). The pallets in the soundboard, because of the proximity of the blower, were affected by turbulence and vibrations from the impeller - and this was transmitted through the action to the keyboard. This characteristic reinforced a basic organ building rule that fans should be placed as far away from the instrument as realistically possible, in order to allow the air flow from the fan to the pipes to be as smooth as possible.

Even after removing the fan, the problem of flutter, ripples and unsteady pitch still remained in the tonal characteristics of the organ. In 1990 a fan regulator (air reservoir) was installed to steady the air flow. It was found to make no audible difference to the tonal quality of the instrument since when the air inlet to the reservoir was open (when the organ was played) turbulence passed straight to the organ itself.

In 1991 the 12 radial blades of the impeller were replaced by 24 backward facing blades (together with a new 3 phase ac motor). The impeller speed was unchanged. The wind output was increased by 50%. These changes gave some improvement but not a complete solution to the problem. The notes now affected by flutter and ripple were shifted upwards by an octave, suggesting that the sound of the pipes was affected by the quality of the wind.

What emerged from the foregoing previous work on the organ was that the complete solution to the problems emanating from the wind supply was not obvious. Working towards a complete solution to the problem therefore required that the turbulence situation in the organ wind system be studied.

1.3 An overview of the Organ and Organ Pipe

Figure 1.1 and 1.2 gives a block diagram of a typical organ pipe and organ respectively.
When the player’s hand exerts wind from the fan, it flows through the windway of the organ. A valve, known as a pipe foot hole, is inserted into the pipe to allow air to pass through. The pipes are connected at the toe/foot hole or bevel. The windway directs the air to the pipe mouth, allowing it to pass through the pipe foot hole. If the stop is not open, the wind path is blocked, and air cannot enter the pipe.
Switch normally on at console for turning on/off fan

Organ Blower
Fan

Wind Flow Valve

Wind
Flow

Wind Reserve

Sound Board
Organ Pipes

Feedback between reservoir and valve. Valve automatically opened/closed as wind demand increases/decreases respectively

Organ Console

Pipes are stationed on the sound board. Pipes are actuated from the the console (keyboard)

Figure 1.2 Basic block diagram of the organ

When the blower is switched on, wind from the fan is fed to the pipes through the reservoirs. Air into the sound board comes in via a valve, reservoir and wind trunk. The pipes are situated on the sound board. Wind is released into the pipe via the pipe foot hole (cf figure 1.1) when the corresponding key and stop of that pipe are operated at the console. The wind flows downstream of the pipe foot (cf figure 1.1) through the windway into the pipe body where it produces sound.

When a note is played, the key opens a pallet (valve) at the base of the soundboard to admit wind into the note channel. If a stop(stops) is drawn, the wind path from the note channel to the pipe foot is open and wind can flow from the note channel to the toe hole of the pipe. If the stop is not drawn, the wind path is blocked and air cannot get to the pipe

1. Details of an overall view of the soundboard are given in appendix 2
foot. This kind of sound board is the slider soundboard since the movement of a slide by
the stop is the final control on the wind supply before it enters the pipe. An annotated
diagram of the sound board is in appendix 2.

The sound production mechanism has been studied by many. One of the studies conducted
by Yoshikawa & Saneyoshi\textsuperscript{98} suggested that a "feedback process" at the mouth area of the
pipe sustains stable oscillations within the pipe resonator. Using a diagram similar to figure
1.3 below, Yoshikawa & Saneyoshi explained that when air jet from the windway hits the
upper lip/edge of the pipe, a pressure difference across the air jet, $\Delta p$, induces a lateral
displacement on the jet, which in turn produces an excitatory source $Q_e$, by switching the
jet as it impinges on the edge. $Q_e$ yields an acoustic volume velocity at the mouth $Q_m$ and
pipe, $Q_p$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig13.png}
\caption{Schematic to illustrate the sounding mechanism of organ pipe}
\end{figure}

Another generation mechanism explained by Davies\textsuperscript{103} and others\textsuperscript{104}, relies on vortex
sheets produced at the upper lip of the pipe to excite the pipe resonator. When the jet from
the windway impinges on the upper lip, the flow separation from there produces a shear
layer/vortex sheets that serve as an excitatory source for the pipe resonator. The sound in the resonantor interacts with the vortex sheet synchronising it to produce "an ordered train of vortices" which in turn produce self sustained oscillations. It is possible that both mechanisms outlined above contribute to the sound excitation mechanism.

1.4 Thesis outline

A study of the historical evolution of organ blowing equipment was undertaken and a brief account is presented in chapter 2. Organ blowing machinery had evolved over the centuries from human operated bellows to today's centrifugal blowers. The evolution from one system to another has been driven by the inadequacies of the blowing machinery in use at the prevailing time. Which ever type of blower was in use at a particular time, the primary objective was to meet the wind demands of the organ in question within an instant without any unwanted audible effects such as jolt, jerkiness, flutter and loss of pitch due to inefficient supply or pressure. Early electrically driven organ blowing systems produced smooth air flow but at low efficiency and high financial and space costs. Developments have reduced these two demands but have compromised wind quality.

In chapter 2, the advantages and disadvantages of the blowing machinery presently in use in organ blowing circles, the centrifugal blower, is discussed. It is proposed that the fundamental weakness of the centrifugal blower is its propensity, when operating at a high efficiency, to generate turbulence, which it is believed, detracts from the quality of organ pipe sound. Modifications, prior to this study, to the centrifugal blower to significantly curtail this defect had not been completely successful. This prompted the need for this research to explore other ways and means through which turbulence could be suppressed and or attenuated.

Chapter 3 contains a discussion of the various techniques for attenuating or suppressing
turbulence. Methods of reverting turbulent flows to laminar or near-laminar flow and postponing the onset of turbulence are given. These techniques include; channel enlargement, channel spanwise axis rotation, helical wound wind trunks, curved flows and flow stratification. Most of these techniques work for flows with Reynolds numbers below 20,000. Flows in wind trunks supplying wind to organs generally have Reynolds numbers in excess of 50,000. The technique of flow stratification could handle flows with very large Reynolds numbers and will be used to attenuate turbulence.

An attenuator was designed and built to be used for St. Paul's organ blowing system. This was tested in the laboratory (University of Huddersfield) prior to installation. It will be shown, via spectral analysis, that the attenuator significantly attenuated the turbulence in the flow by up to 30dB. Differences in the organ pipe notes played with turbulent and turbulent attenuated wind will be demonstrated through qualitative and quantitative analysis.

The spectrum of pipe sounds recorded when played with the turbulent attenuator connected and disconnected are shown in chapter 4. An aural evaluation of the notes played with and without the turbulence attenuator is also discussed. Similar experiments were repeated in the laboratory using pipes on the windchest of a test rig. It is shown in chapter 5 that the improvements encountered in the St Paul's Hall organ were also realised in a laboratory environment.

In chapter 5 a model is developed (which supports experimental results) to provide a quantitative evaluation of changes in pipe note when played with wind of different turbulence flow conditions. The technique used is based on adaptation of the principles of statistical moments about some reference point. The skewness (deduced from the 3rd moments) and the peakedness or kurtosis (deduced from the 4th moment) will be evaluated. It was demonstrated through experimental results that the peakedness and
skewness change and that the frequency of the notes tend to shift with changes in flow conditions.

In research conducted elsewhere to study the dynamics and aero-acoustics of the organ pipe and note channel, the researchers have resorted to electrical circuit models of the pipe or section of the organ under study to assist with their analysis. A linear equivalent circuit model of the organ pipe was developed for turbulence studies in chapter 6.

Chapter 7 discusses areas where further developments and research can be conducted as well as other applications of this research. Most of the studies on the organ pipe have been applied to understanding the aero-acoustics of fluid pipelines and other wind instruments. Some of the findings here could be applied to research in these sectors.

In the final chapter, chapter 8, the concluding remarks are presented.
CHAPTER TWO

A REVIEW OF ORGAN BLOWING MECHANISMS

Organ blowing machinery has had a colourful History. What ever their nature organ blowers had to provide wind pressures ranging from 350 Pa to over 5000 Pa$^2$, and maximum volumes required over a similar range. Today a typical new organ will be operating at about 2000 Pa requiring wind flow in the region of 0.7 m$^3$/s.

The blowers used ranged from the human operated blowers, through hydraulic blowers and gas engines to centrifugal blowers. The ensuing sections discusses the principal types of blowers that have been in use so far.

2.1 Manual Blowers

These blowers involved the distension and compression of bellows by hand and/or foot, as per figures 2.1 and 2.2.

Bellows that were, and are still, used in organs are similar to the lungs in operation, except that in lungs there are no valves and air comes in and goes out the same way. The similarity are more pronounced during distension. When the wall(s) is(are) distended, air is sucked in through a valve(s). On compression, the valve(s) is(are) closed and the air is forced out into the reservoir and downstream via the trunk(duct) into the wind chest or soundboard.
Human operated blowers provided relatively smooth wind, however, large volume and high pressure demands required prolonged stamina and a sizeable human labour force. The first organ built in Winchester Cathedral, (circa AD951) had 400 pipes and 26 bellows that had to be operated by hands and feet of "... 70 strong men."\textsuperscript{24, 35} Clearly the logistics of labour force requirements posed a fundamental restriction on the size of organ that could be built and upon its utilisation.

Few organs are manually blown nowadays. Of over a dozen organs visited as part of this work, one, Thurstonland Anglican Church, West Yorkshire, had a dual blowing system: a manual blower and a centrifugal fan.
2.2 Hydraulic Blower

The application of hydraulic power in organ blowing machinery dates back to the Victorian age (i.e., c1850-c1914). The hydraulic blower consisted of one or more cylinders with a piston inside each of them. The cylinders had two vents - with valves attached to both: one at the water inlet and the other at the outlet. By varying the water pressure on either side of the piston, it was moved up and down (or left and right for horizontal systems). The (reciprocating) piston compressed and distended the bellows. The piston was actuated by the controlled injection of water above and below the piston via the controlling valves. The pressure differential across the piston moved the piston in one direction or the other.

As the piston moved up and down, it compressed and distended bellows - the bellows sucked air in via its inlet valve, while the outlet valve is closed. On the downward stroke the inlet valve is closed and the outlet valve forced open by the wind pressure, forcing the wind downstream into the wind reservoir and trunks into the soundboard. The system had provision for a leakage valve for situations where the air reservoir was full and further wind input was superfluous.

![Figure 2.3 An example of a hydraulic machinery used for organ blowing (Courtesy of Elvin)](image)

The principal advantage with hydraulic operated blowers, was their quiet operation, attributed to their slow speed (about 50 rpm). The wind generated was not very turbulent relative to latter day ones.
Water mains controlled hydraulic blowers had one major disadvantage: there were variation in the mains water pressure which could cause operational difficulties. In fact the cost of maintenance turned out to be more than the cost of the equivalent centrifugal fan.70

2.3 The Gas Engine

After the hydraulic machines came gas engines. These were mainly in use during the late 19th and early 20th century.88 The combustion of a gas mixture in a cylinder, released Energy which in turn was used to drive a piston(s) that were attached to bellows via cranks. The compression and distension of the bellows supplied wind into the organ. In some organs, the kinetic energy of steam was used. Around 1860 (and up to the 1920s) the organ in St. George’s Hall, Liverpool used a steam engine of 1.9 kW - 2.5 hp (and later 6kW, i.e. 8 hp) to supply up to 5500 Pa (22 inH2O) of wind pressure.24 The gas engines were bulky, and had to be kept at long distances from the organ. Furthermore, the fumes and oil from the engine were inevitably sucked into the bellows with damaging and costly consequences.

2.4 The Centrifugal Fan as an Organ Blowing Machine

Early versions of the centrifugal machine were introduced in the organ blowing circle as Kinetic Blowers.

2.4.1 The Kinetic Blower

Basically this is a brand of multistage impeller centrifugal machine where all the stages are in the same casing, with each stage separated from the proceeding and/or proceeding stage by a plate with a circular orifice cut out at the centre of this plate to clear the main
shaft. Air compressed at the edge of the first set of impellers is channelled to the centre of the next set of impellers on the same shaft, as a consequence, progressively increasing the pressure of the wind. Where required, wind can be tapped off after any impeller stage.

Such blowers are still in use today. The blowers of the Anglican Liverpool and Durham Cathedral Organ and St. Peter’s Parish Church, Huddersfield, are some of many examples. The Liverpool Anglican Cathedral organ is blown by three kinetic blowers: two operating at 1440 rpm at 13.5 KW (18 hp) and the other at 1400 rpm at 9.4KW (~12.5 hp). (These are rated values). Each occupy a space of about 3 m by 0.70 m by 0.8 m; delivering a sum volume of about over 3.33 m³/s and an overall wind pressure of 5500 Pa. A comparable organ in St. George’s Hall in Liverpool, uses two centrifugal blowers rated at 2.83 m³/s flow rate, 12.5 KW and 0.233 m³/s at 12 KW, both running at 1450 rpm. These machines have outer diameters of 1.5 m and 1 m diameters respectively; while both have a breadth of 0.25 m. These devices were large, noisy and expensive to run. They also require large and expensive reservoir system to support them. Advances were therefore sought that were small cheaper and less expensive to operate. The centrifugal blower offered gain in all these areas.

2.4.2 The Centrifugal Blower

The centrifugal fan is much smaller and more efficient than a kinetic blower, for a given wind demand specification.

Air sucked in via the inlet of the centrifugal blower is imparted kinetic energy by the moving blades of the impeller and the pressure rise is then achieved by diffuser action as the air flows in the casing (and diffuser where present). This is known as dynamic compression.  

Where a single stage fan can not meet the pressure requirements of a specific organ, several centrifugal blowers are used in cascade: the output of one feeding the input of the
next machine in the cascade. The final output or output tapped off at intermittent stages are then channelled off, via a reservoir, through appropriate trunking into the organ soundboard.

Between the blower and the reservoir, there usually is a regulator, regulating the volume flow rate into the reservoir according to demand. The valve used, undoubtedly introduces extra turbulence in the wind and is likely to influence the acoustics of the organ pipe.

2.4.3 Advantages of the Centrifugal and Kinetic Blowers

a. They are very compact machines.
b. They have no valves and hence fluctuations in pressure which may arise from valve motion are absent.
c. Mechanical balance is easily achieved as the construction is mainly axi-symmetrical in structure, inherently resulting in less mechanical vibrations.
d. Because direct motor drive of the centrifugal machine is possible, gear noise is avoided.
e. These blowers require minimal maintenance.

2.4.4 The Disadvantages of the Centrifugal and Kinetic Blowers.

In spite of the several advantages of the centrifugal blower, they have disadvantages for organ blowing purposes.

Among the disadvantages are:

a. The process of raising wind in the centrifugal blower, is by dynamic compression; involving the conversion of a velocity head into a pressure head. This generally yields a temperature rise which tends to increase with decreasing efficiency;
b. Centrifugal machines raise wind that has pressure fluctuations which are dependent on the rotational speed and impeller blade count of the machine. Guelich and
Bolleter\textsuperscript{38} have studied and discussed the effects and mechanisms of pressure pulsations in other applications, wherein it is proposed that there are two principal types of pressure pulsations that matter:

i. those that have discrete frequency peaks, and
ii. broadband pressure fluctuations (i.e., flow noise and turbulence).

Pressure pulsations with discrete frequency peaks are determined by the Blade Rate Frequency and the Blade Pass Frequency.\textsuperscript{19,37,38}

c. The flow path from the inlet to the outlet of the centrifugal machine involves a complicated and contorted geometry, which generates considerable turbulence and pressure fluctuations. It has to be mentioned that pressure fluctuations are different from turbulence: the former is not random and covers a wider range on the frequency spectrum. The finite number of blades and the eddy separation at the blade tips gives rise to pressure fluctuations.

d. Basically, the overall machine concept wherein rotating blades are enclosed within a confined space is inherently a turbulence generating situation. This further makes it difficult to design a low turbulent wind supply using a centrifugal machine;

d. There is a conflict of requirements for smooth flow dynamics and for high pressure. The centrifugal machine is principally a low pressure rise machine; typically 250Pa to 5,000Pa in a single stage.

The pressure head, $P$, is generated by converting a velocity head, due to a bulk velocity of $U$, as given in the basic equation outlined below, assuming no viscous effects.

$$P = \frac{(pU^2)}{2} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdOTS_17_0
Number, $R_e$; where

$$R_e = \frac{(\rho UD_e)}{\mu}$$

\(D_e = \text{a characteristic length dimension, hydraulic (equivalent) diameter and}\)
\(\mu = \text{viscosity of the fluid.}\)

Where:

$$D_e = \frac{4 \times \text{Duct Area}}{\text{Duct Perimeter}}$$

2.5 Surmounting the defects of the Centrifugal Machine

There are two possible ways of tackling the short comings of the centrifugal fan. The two approaches are:

a) minimising turbulence through design and/or
b) eliminating the turbulence down stream.

The first method is discussed in the ensuing section, while the later will be treated in more detail in chapter 3.

2.5.1 Modifications to the Impeller Blade Geometry

The different configurations (see figure 2.4) of the centrifugal machine impellers include:

a) forward facing impellers;
b) backward facing impellers and
c) paddle (radial) impellers.

The shape of the blade used in most applications depends on the pressure rise, flow rate and impeller diameter required.

In many organs, the centrifugal machine providing the required wind have radial blades. The modifications on the impeller geometry involed using backward facing blades with a
Why use backward facing blades? This question will be answered with the aide of figure 2.4 overleaf. An examination of the pressure versus volume curves of the different blade geometries indicate that the backward facing blade provides the most stable operation. The pressure versus volume curve of the forward facing blade impeller (fig 2.4, II-a) shows some non-uniformity in the changes in pressure with increasing volume. There are operating pressures that have two and even three possible volumetric flow rates. Operating the fan at such pressures may result in instabilities that cause stalling. The Paddle/Radial bladed impeller configuration also has a non-uniform pressure versus volume curve (c.f. fig 2.4, III-a). As the volumetric flow rate increases, the pressure increases before falling. At certain operating pressures, there are two possible volumetric flow rates. Operating the radial bladed centrifugal fan at such pressures can result in stalling. Judging from the pressure versus volume curve of the backward bladed centrifugal fan (c.f. fig 2.4, I-a), it can be inferred that at any operating pressure, there is only one volumetric flow rate. This uniform pressure versus volume flow characteristic is what gives the backward facing bladed impeller fan its operational stability and superior performance relative to the other blade configurations, they are also more efficient and give rise to less turbulence. It has to be said that efficiency is not necessarily an advantage. In chapter 4, section 4.3, this will be dealt with further further when a discussion on some experiments with a blower borrowed from Harrison & Harrison Organ Builders, Durham, is given.

Another modification of the blade geometry involves the use of a split impeller configuration. This is especially so for large pressure rise applications. The split blade geometry increases the radial depth of the blade which helps in reducing the boundary layer separation around the blades, thereby also reducing the formation of eddies that do induce turbulence. Plate 2.1 depicts a modified impeller geometry that is in use in the centrifugal machine in St. Paul's Hall, University of Huddersfield.
Chapter Two: A Review of Organ Blowing Mechanisms.

Fig. 2.4: Graphs Pairs I-a, II-a, III-a, are Static Pressure vs Volume and Sound Pressure Level vs Frequency for I-b; Backward Facing Blades II-b: Forward Facing Blades and III-b Paddle (or Radial) Bladed Impellers, respectively
The aforementioned improvements of the blade geometry have been implemented in a centrifugal machine designed and fabricated within the University. The improvements achieved do not go far enough in alleviating the fundamental problems of unsteadiness, flutter and ripple in the acoustics of the organ pipe. Indicating that the problem of turbulence persists.

Plate 2.1 Impeller geometry of centrifugal blower in St. Paul’s

This impeller configuration shifted the turbulence problem upwards by one octave, i.e. doubling the frequency, on the organ in St. Paul’s Hall, University of Huddersfield. This is due to the doubling of the number of blades previously used from 12 to 24. It becomes
increasingly clear therefore that pursuing further improvements on the centrifugal machine for the application of interest in this research may only lead to a further marginal improvements. Some experiments carried out, indicate that the level of turbulence in the flow depends on the operating point on the efficiency versus flow rate curve of the Centrifugal Blower in use (will be discussed in chapter four).

An innovative solution to this problem was to consider designing a machine centred on new concepts apart from the centrifugal machine. Before that, another remedy for the turbulence situation was considered: that of minimizing the turbulence generated by the centrifugal machine. The research work pursued this avenue as will be discussed in the next chapter.

The development of the organ blowing systems can therefore be summarised in the chart in figure 2.5.
Chapter Two: A Review of Organ Blowing Mechanisms.

Fig 2.5 Flow diagram of organ blowing machinery

- Power sources
  - Electricity
  - Human
  - Steam
  - Gas
  - Hydraulic

Methods of Compression

Energy converted into kinetic energy, yielding air motion.

- Positive displacement
  - Compression & distention of feeder bellows supplying wind to a reservoir
    e.g. Hydraulic blower

- Dynamic compression
  - Blowing of air into a storage reservoir
    e.g. Centrifugal blower
CHAPTER 3

TURBULENCE SUPPRESSION AND ATTENUATION

3.1 Principles of Turbulence Attenuation and Suppression

A distinction has to be made between turbulence attenuation and turbulence suppression. In the latter case, the flow is controlled to avoid the generation of turbulence or to delay the onset of turbulence. In the case of turbulence attenuation, turbulence already within the flow is reduced, or eliminated so that the flow becomes laminar.

Several techniques have been exploited in suppressing turbulence in fluid flow. Theoretical analysis as well as experimental investigations have been conducted by Sreenivasan and Strykowski; Narasimha and Sreenivasan; Sreenivasan; Manlapaz and Churchill; and Viswanath. Using the equations of conservation of momentum and mass; Narasimha and Sreenivasan deduced that the turbulence energy, , consisted of five categories, namely:

i) Energy generated by Reynolds stresses
ii) Work done against fluctuating body forces
iii) Viscous losses - ie the conversion of Kinetic Energy into Thermal Energy
iv) Viscous diffusion and
v) Diffusion due to pressure and turbulent fluctuations.

1. A theoretical overview of turbulence is outline in appendix 3 together with a discussion on method of analysing turbulence for the for the purposes of this work.
Techniques that contributed to minimise $q$, would result in relaminarization.

It turns out that the decorrelation of the principal velocities that directly contributed to the level of the Reynolds stresses contributed significantly in reducing turbulence. This concept shall be treated in more detail in subsequent sections.

Parameters used to determine the onset of relaminarized flow were:

- cessation of bursting,
- change in the stress gradient at the wall,
- fall in the skin friction,
- fall in Reynolds numbers to below its critical value,
- flow profile approaches the laminar velocity profile and
- a drop in the heat transfer coefficient.

Photographs of turbulent to laminar reversion in fluid flow as well as oscillograms of Hot Wire Anemometer traces were given to corroborate experimental findings. Manlapaz and Churchill on their part carried out detailed studies on skin friction and the helical number (the modified Deans number) to study relaminarization in helically coiled channels of finite pitch.

The investigations of the researchers cited principally concluded that there are three methods of turbulent to laminar flow reversion, namely: dissipative reversion, Richardson type reversion and reversion by domination.

3.1.1 Dissipative Reversion.

In this process, molecular transport agents, e.g., friction, causes the loss of turbulence energy, demonstrated by the changes in the Reynolds number. Pipe flow experiments conducted by Narasimha and Sreenivasan concur that the weakened Reynolds stresses
indicated that the turbulence energy has been attenuated.

3.1.2 Richardson Type Reversion (Dissipation via Stabilized Stratified Flows)

Here turbulence is suppressed by a “stabilizing density gradient” as proposed by Richardson circa 1920. This can be demonstrated by injecting a strand of dye in a water tank of uniform temperature. The dye is injected at the base and allowed to flow towards the ceiling. The flow is observed to be turbulent as it progresses downstream.

If the top of the tank is heated, such that the water nearer the ceiling becomes hotter and less dense relative to the base, the strand of dye flowing upwards towards the ceiling now has the perilous task of working against the density gradient: the turbulent energy of the dye is now converted into gravitational potential energy. This dissipation of turbulence energy yields reversion from turbulent to laminar flow. Viswanath and Sreenivasan took some pictures illustrating this phenomenon.

This phenomenon also occurs in the atmosphere when turbulent smoke reverts to laminar flat clouds as the smoke moves towards the stratosphere. The hot atmosphere nearer the sun and the cooler earth surface (cooled by convection currents) leaves a density gradient not conducive for sustaining turbulence flow - hence the turbulence suppression.

3.1.3 Reversion by Domination.

This occurs when a turbulent boundary layer is subjected to strong streamwise acceleration. Viswanath have conducted experiments with supersonic flows to demonstrate this type of reversion. Narasimha and Sreenivasan found evidence of decorrelation of the velocity components that determined Reynolds stresses. They also noted that there was a drastic fall in the skin friction. The foregoing corroborate the retransition into laminar flow. Here the observation of relaminarisation was principally in the boundary layer and not within the entire flow. This kind of reversion is found to be dominant in flow reversion that takes place in helically coiled ducts.
3.2 Some Techniques used to realise reversion.

Some of the techniques used include: curved flows, spanwise axis rotation of the flow channel, helically wound ducts and channel enlargement.

3.2.1 Curved Flows

The diagram of figure 3.2 gives an illustration of the process involved.

![Diagram of curved flows](image)

**Fig 3.2 - Schematic diagram to demonstrate reversion by means of curved flows**

The incoming flow at the centre is converted into outward radial Poiseuille Flow between the two parallel discs. It turns out that the $R_e(r)$ at a radius, $r$, from the centre of the feeder pipe is inversely proportional to, $r$, and directly proportional to, $a$, the pipe radius.  

3.2.2 Turbulence Attenuation via Spanwise Axis rotation of the Flow Channel

Flow visualisation techniques have been used to illustrate that turbulent flow reverted to near laminar flow especially near the walls. The skin friction was found to have dropped significantly. Narasimha and Sreenivasan's experiments were conducted with flows that have $R_e$ not exceeding $2 \times 10^4$. 

...27...
3.2.3 Channel Enlargement

Laminarisation is realised by gradually enlarging the wind trunk from a smaller to larger (hydraulic) diameter (cf Fig. 3.3), while ensuring that the half angle of divergence, \( \theta \), is small enough to avoid flow separation.

\[ D_u = \text{upstream diameter} \]
\[ D_d = \text{downstream diameter} \]

*Fig 3.3 Reversion due to channel enlargement*

Experimental results reported by other researchers and cited by Sreenivasan$^{84}$ illustrate an attenuation in turbulence by as much as 80%, for half angles of deviation, \( \theta \), of 1° and 3°. Channel enlargement is believed to be a typical example of dissipative reversion.$^{64}$ The velocity profile was found to approach the Poiseuille solution$^{64}$ downstream after the enlargement. Add to that, a drop in skin friction. Narasimha and Sreenivasan,$^{64}$ further noted from experimental measurements that at 20a and 180a downstream, after the enlargement, the correlation coefficient of the two dimensional (x and y) velocity components fell from 0.36 to 0.13 (~70% attenuation) respectively. They thus concluded that a "decorrelation mechanism" was destroying the "coherent motions" and weakening the Reynolds stresses, with the net result that turbulence was being destroyed far more than it was being created.
3.2.4 Turbulence Reversion using Helically Coiled Pipes

By using helically coiled pipes as depicted in Fig 3.4 below, turbulent flow has been shown to revert to laminar flow. Re-conversion to turbulent flow further downstream, occurred, at much higher critical Reynolds numbers. \(^5\)\(^4\) \(95\) \(^5\)\(^9\)\(^8\) \(^5\)\(^9\)

Viswanath, \(^95\) conceded that though the reversion process in these types of flow have been known since the 1920s, there was still a lot of ambiguity surrounding it, however, they did postulate that it could be due to the Richardson effect - a change in density gradient between the inner and outer wall. It can be inferred from experiments conducted by Manlapaz and Churchill, \(^5\)\(^4\) and the arguments of Narasimha and Sreenivasan, \(^6\)\(^4\) that a combination of the Richardson effect and suppression by domination are taking place in the flow. The faster flow in the outer wall dominates the turbulent fluctuations taking place in the inner wall.

**Fig 3.4 Turbulence reversion in flow through helically coiled pipes.**
3.2.5 Turbulence attenuation by flow stratification

If the fluid flowing upstream is conveyed from one large channel to several narrower ducts, with significantly smaller hydraulic diameters, the Reynolds number of the flow could be reduced significantly. The narrow ducts are stacked next to each other.

The total area of the narrow channels being equivalent to the area of the preceding duct.

The narrower channels on the whole tend to take up a greater area because of their wall thickness: this makes it necessary for outer walls of the duct to be gradually enlarged to accommodate the strata of narrow channels. After the stack of narrow channels, the duct is again narrowed down to its original dimensions upstream.

![Fig. 3.5: Section of schematic for turbulence attenuation by stratified flow](image)

The strata of narrow channels can be a stack of honeycombs or tiny polygonal ducts. The channels should be sufficiently long enough to attain steady flow conditions: i.e. the length should be at least 20 times the hydraulic diameter of the narrow ducts.

So if the dimensions of the trunk went from say 20 mm by 20 mm in the main trunk to say
3 mm by 3 mm in the rectangular “honeycomb”, there would be a change in hydraulic diameter from 20 to 3 respectively. The change in hydraulic diameter would yield a proportionate change in the Reynolds number.

If the narrower channels have a wall thickness of 500µm, say, then the main trunk would have to be enlarged to 625 mm² from 400 mm² to accommodate a strata of narrow channels with identical flow area.

3.2.6 Choice of turbulence attenuation or suppression technique

Where curved flows are used to realise reversion, reversion has been demonstrated for flows with Reynolds numbers (Re) not exceeding $10^4$. Much less than the turbulence conditions experiences in organ blowing situations, where $Re$ in excess of $5 \times 10^4$ are encountered.

In organ blowing situations, the ducts have large hydraulic (equivalent) diameters and are, made of clay or wood in most cases. Spanwise axis rotation as a means of curbing turbulence would prove unwieldy and not cost effective.

Channel enlargement techniques used in realising relaminarization have been shown to work for $Re < 13000$, a rather small $Re$, compared to Reynolds numbers encountered in organ wind supply systems.

The experiments conducted to study reversion in helically wound ducts process have been done with radius ratios: $a/r$, of less than 0.1. The technique was found to be valid for maximum upstream Reynolds numbers of less than $10^4$. Further downstream if re-conversion (retransition) into turbulence flow occurred, it did so at a much higher critical Reynolds number of $\sim 5200^{85}$.

Typical organ wind trunks supplying church and hall organs with wind tend to have diameters in the neighbourhood of 200 mm or more. To achieve a radius ratio of less than
0.1, would require a coil radius, \( r \), of greater than 2000 mm. There is hardly such large space to spare for trunking within organ systems. Besides their wind supply Reynolds number of upstream flow is in excess of \( 10^4 \).

Realising that many of the prevailing schemes for attenuating or suppressing turbulence are not suitable for organ applications, the technique of turbulence attenuation by flow stratification was adopted.

In determining whether turbulence had been attenuated to revert to laminar or near laminar flow conditions, the energy spectral density and the time domain oscillographs of the turbulence signal were measured, before and after the attenuation process, with a hot wire anemometer. The Reynolds number before and after attenuation was also evaluated. The hot wire anemometer could only measure turbulent fluctuations in one dimension, meaning that we could not evaluate the correlation of the principal velocities in 2 or 3 dimensions. The instrumentation for measuring boundary layer bursting and skin friction were unaffordable or unavailable. Though other sophisticated measuring instrumentation could have been used, the hot wire anemometer was adequate for the application in hand.
CHAPTER FOUR

EFFECTS OF TURBULENCE ATTENUATION

4.1 The Turbulence Attenuator (Filter)

The turbulence attenuator was designed for the St Paul's Hall organ to reduce the Reynolds number of the flow without compromising the flow rate. The method that will be proposed also seeks to decrease the scale/intensity of turbulence by decreasing the space over which the "random motions" of turbulence can fluctuate and hence its fluctuation amplitude thereby realising reversion by dissipation.

The turbulence attenuator was made up of a stack of small rectangular "honeycomb" passages of length $L_w$ where $L_w$ is chosen such that a steady flow is obtained downstream of the stack length before the wind exits the attenuator.

The rectangular passages in use have an area of 8.22 mm$^2$. The leading edge of the duct into the entrance of the attenuator was gradually expanded to accommodate the increase in area due to the wall thickness of the narrower channels. The channel expansion decreases the flow speed and increases the pressure of the wind before it gets into the passages. This also helped to compensate for the very small, but extant, decrease in pressure (found to be less than 50 Pa; ie less than 0.2 inches H$_2$O) that comes with the increased wind speed as the wind flows downstream into the passage. After the honeycomb, the duct is funnelled down to its original dimensions. The angle of the leading and trailing funnels were both less than 10° so as to minimize any flow separation, especially after the honeycomb (see fig. 4.0 below) Fig 4.0 depicts the attenuator (with an $L_w$ of 100 mm) designed for the St. Paul's Hall organ.
It is speculated that the flutter and ripple on sustained notes at certain stops on the organ are due to the turbulence in the wind flowing into the soundboard. Experiments carried out to investigate the influence of turbulent wind on the quality of organ sound will be described in chapter four. Ideally this should be done by taking measurements (recordings) of some pipe sounds at wind possessing different levels of turbulence flowing into the soundboard.

The first phase of this scheme involved introducing the turbulence attenuator outlined above in the path of the wind and qualitatively analyse whether any improvements in sound quality have occurred. This was done by comparing the spectrum of the sound of the organ pipe under investigation before and after the attenuator was installed.

Fig. 4.0: Turbulence attenuator built for the St. Paul's Organ, Univ. of Huddersfield.

Note: Not to scale
All Dimensions are in mm
4.2 Evaluation of the Turbulence Attenuator

Flow velocity and turbulence measurements were made on a test rig in the laboratory with wind supplied by a centrifugal blower that has a flow rate of 0.6 m$^3$/s (i.e. 1200 ft$^3$/min.); driven by a Brook Crompton 1.5 KW, 3 phase motor. This is identical to the blower in use in St. Paul's with the exceptions that the blades were radial, and the finish inside of the casing was coarse. For the given duct dimensions, this meant a mean flow velocity of 9.258 m/s and a duct hydraulic (equivalent) diameter, $D_e$, of 216.5 mm. (The details of these calculations are given in appendix 4). Using $1.8 \times 10^{-5}$ Ns/m$^2$ and 1.2 Kg/m$^3$ as the viscosity, $\mu$, and density, $\rho$, of air respectively, an $Re$ of 133723 is obtained (calculated with the help of equation 2.2). This being the Reynolds number of the flow before the attenuator was introduced.

The attenuator constructed was inserted in a portion of the wind duct. The duct internal dimensions of the St. Paul's organ are 419 mm by 146 mm. The inlet and outlet dimensions of the attenuator was built to match the duct internal dimensions.

To satisfy the condition of steady and developed flow; a duct length of 2.4 m, (over 10 times the hydraulic diameter, $D_e$) was used. Turbulence spectral measurements were made of the wind just before the exit of the straight duct. Comparative measurements were taken after the attenuator designed for St. Paul's was attached at the end of this duct.

As the wind flowed down stream through the attenuator, the wind mean velocity through the "honeycomb" increased with an associated pressure drop $\Delta p$, where $\Delta p$ is given by equation 3.11 below;

$$\Delta p = \frac{4(\rho f L_{o} U_{p})}{2d_e}$$

4.1
with \[ f = \frac{16}{Re} \] for laminar flow conditions
and \[ f = \frac{0.079}{(Re)^{0.25}} \] for turbulent flow

where \( f \) = friction factor, and \( U_p \) = mean flow velocity in passage.

With the "honeycomb" dimensions of 2.4 mm by 3.5 mm, \( \Rightarrow d_e = 2.85 \text{ mm} \), yielding a Reynolds number, \( Re \), of 1085.

\( Re \) has decreased by a factor of more than 120; transforming the flow into the laminar flow regime.

The turbulence reduction is at the expense of a small pressure drop, calculated from equation 4.1 to be 40.62 N/m\(^2\), (in organ builders language: 4.14 mmH\(_2\)O or 0.163 inH\(_2\)O). Using a TECquipment AF10 multitube manometer, a pressure drop of 0.4 mbar (\( \approx 40.53 \text{ N/m}^2 \)) was measured across the "honeycomb", in agreement with theoretical calculations.

4.2.1 Choice of Flow Measurement Equipment

Several measurement systems do exist with different forms of sensors for measuring turbulence motions. The HWA technique used is just one of several techniques that uses a probe operating on electrical principles.

*The thermistor* operates on similar principles to the HWA. However its poor sensitivity and unpopularity in measurements systems required for such application ruled it out. \(^{41}\) Other electrical probes exploit *electrochemical and electric discharge* techniques which make them more suitable for liquid than gaseous applications.

Mechanically based probes include: *the total head tube*, based on the hypodermic needle with a pressure transducer at one end. Unfortunately the needle behaves like a resonator usually requiring compensation for or annulment of these effects. The multiplicity of
coupled systems involved: acoustic, mechanical and electrical systems together with their low frequency response (typical bandwidth of 3KHz\textsuperscript{41}), makes this approach a complicated and unsuitable choice for our measurements.

Other mechanical systems like the static pressure tubes amongst others could not be used because of their unnecessary complication relative to the application and/or low frequency response: usually less than 5 KHz.

Most contemporary flow measurement techniques do involve some form of flow visualisation, e.g. the Hydrogen bubble technique, light refraction techniques, others that take advantage of the absorption and scattering of light by the fluid etc. These techniques were not used because of their bulkiness, prohibitive costs and complexity relative to application in hand.

With the other schemes discounted, the HWA was resorted to. In Hot Wire Anemometry, there is the Constant Current and the Constant Temperature approach. Though the former is the simpler method, however, the wire time constant (impulse response) and hence frequency response, changes with change in operating point,\textsuperscript{41,65} making the constant current approach undesirable. Add to that, there are very few manufacturers of the Constant Current Anemometer. The constant temperature HWA is much simpler to use. Furthermore, its sensitivity does not change significantly with the operating point of the device, hence its use in our measurements.

4.3 Fluid Dynamic Evaluation of the Turbulence Attenuator

4.3.1 Spectral measurement of turbulence

The turbulence spectrum of the wind from the duct attached upstream to the centrifugal machine was measured using a film type Hot Wire (HWA).
The turbulence spectrum was measured with a TSI 1210-20 HWA (from BIRAL UK Ltd., Bristol, TSI's UK representative) film probe placed in contra flow to the wind flowing downstream. The probe was connected to a TSI constant temperature anemometer bridge model 1750 and its output in turn fed into the B&K dual channel spectrum analyser (model 2034). When required, the data displayed on the screen of the analyser was plotted on a Hewlett-Packard HP 7475A plotter. Only data displayed on screen could be plotted. The display scales of the spectrum analyser are not under operator control and hence it was not possible to plot/generate displays which readers will wish to compare to common scales. Hence when reading the plots from the spectrum analyser, attention should be paid on the scale as in some cases it varies. The block diagram of figure 4.1 is a schematic of the experimental setup.

![Block Diagram of Experimental Setup](image)

**Fig. 4.1: Experimental Setup for the Evaluation of the Turbulence attenuator**

Before these measurements were taken, the frequency response of the film sensor was...

..38..
evaluated as prescribed by TSI (appendix 5) and found to have a bandwidth of 50 KHz; implying, the probe can track turbulence motions, fluctuating between 0 Hz and 50 KHz.  

The turbulence measurements were made with and without the attenuator connected. With the probe at the outlet of the duct, the spectrograph of the turbulence signal was evaluated. After the attenuator was installed, similar measurements were again made at the outlet of the attenuator. Prior to these measurements, the spectrograph of still air was measured.

Fig: 4.2- Spectrograph of still air
Fig 4.3- Spectrum of wind before attenuator was installed.

Fig 4.4- Spectrum of wind after attenuator was installed

Figures 4.2, 4.3, and 4.4 are plots of the spectrographs taken: a - still air; b - before attenuator installed and c- after attenuator installed.

Some comments on Figs 4.2 - 4.3

Fig: 4.2- Spectrograph of still air.

This measurement was taken to be used as the reference level (a sort of ground level) for

1. A note on the scale of figures 4.2-4.4

The scale of the spectra are different. This unfortunate occurrence was due to the limitations of the measuring equipment used. (B & K spectrum analyser) The area of screen available for viewing displayed data is limited. The range on the magnitude axis had to be adjusted to bring the data on display into view and so that it could be printed.
other turbulence measurements. The observed still air (reference) level is -60dB (fig 4.2)

- 4.3- Spectrum of wind before attenuator was installed.
Note here that the spectrum has a peak at -4 dB (at 0Hz) falling to the reference (still air) levels of -60dB at 20kHz. This gives a peak magnitude of ~56dB.

- 4.4- Spectrum of wind after attenuator was installed.
After turbulence attenuation, the peak of the turbulence spectrum falls to -23 dB from (-4dB) at 0Hz, rapidly decreasing to the reference level at 3.8 kHz. The peak magnitude has dropped by almost 20dB from ~56dB to 37dB. In addition, after attenuation, some bumps became more prominent on the spectrum, at just over both 500Hz and 1000Hz plus another at 700Hz. The first two are harmonics of the Blade Pass Frequency (BPF), while the 700Hz bump is likely to be due to coupling between the modes of the BPF.

Figures 4.3 and 4.4 show a attenuation in the intensity of turbulence from a maximum of -4 dB to -23 dB. It should be further noted that turbulence is attenuated to still air levels at 3.8 KHz and beyond. 3.8 KHz could therefore be regarded as the cut off frequency of the attenuator. Figure 4.4 further illustrates an average attenuation of turbulence intensity of about 20 dB (a factor of 100) with a maximum attenuation of 30 dB (a factor of 1000) at 4 KHz. All measurements of turbulence were made while the spectrum analyser was programmed to a reference voltage level of 10mV.

It can be argued that the narrowness of the filter channel/passage contributed significantly in curtailing the intensity of turbulence. The boundary conditions changed as the flow went from a wide to a set of narrow channels. The change in boundary conditions caused a restriction in fluctuations and eddie generation. The fall in the Reynolds number meant an increase in the friction factor, and hence increased viscous losses.

This turbulence attenuation technique can be thought of as reversion by dissipation. 64 84 95
From figure 4.3 it can be conjectured that the turbulent fluctuations are predominant at lower frequencies. Figure 4.3 depicts a cut off frequency before installation of 20 KHz when the attenuator was not installed.

4.3.2 Turbulence in the time domain
Figure 4.5 and 4.6 are snapshots of the time domain turbulence signals before and after the attenuator was installed respectively. Figure 4.7 is a more elaborate picture of figure 4.6 - the time domain turbulence signal after attenuation

1. The graphs of figures 4.5 & 4.6 are on different scales also. This adjustment was made so that the data captured on the spectrum analyser could be observed and printed.
There is a similarity in figures 4.5, 4.6 and 4.7 to figure 3.1-i, (repeated below for clarity) of a typical statistically stationary signal: endorsing the presumption that turbulence is statistically stationary. There has been a reduction in the peak to peak amplitude (from \( \approx \pm 20 \) Units to below \( \pm 5 \) Units; a 75\% or 4:1 reduction) of the turbulence time domain signal after the turbulence attenuator.

The performance of the organ in St. Paul’s Hall was evaluated before and after this device was installed will be given in section 4.4.
4.4 Relationship Between Attenuator Honeycomb Length $L_\omega$ and Cutoff Frequency of Turbulence

Four other filters were built to be geometrically similar to the attenuator installed in St. Paul’s, to determine whether there was any obvious relationship between the cut off frequency, $f_0$, of turbulence and the length of the honeycomb in the attenuator, $L_\omega$.

The source of wind used was a B.O.B. Blower (with 12 paddle/radial blades), propelled by a single phase DC drive Brook Crompton Motor, running at 2800 rpm on 0.54 kW (0.75 hp).

Attenuators with $L_\omega$ of 150 mm, 200 mm, 250 mm, and 300 mm, were built. The turbulence spectrum of the filtered and unfiltered wind were taken as earlier discussed and the cutoff frequencies and pressure drops measured. Results obtained are as in the Table I below. Details of their behaviour are as in Figures 4.10, 4.11 and 4.12 below.

The increase in pressure loss, $\Delta p$, with increasing $L_\omega$ is to be expected as $\Delta p$ is directly proportional to $L_\omega$, all the other parameters being equal. The turbulence bandwidth, as expected, grows narrower with increasing $L_\omega$. This is because there is more time over which the eddies have to dissipate their internal kinetic energy as a result of the increased passage length: as would be expected of dissipative relaminarisation.64 84 95

There is also a small but extant pressure drop across the attenuator which increase with $L_\omega$, understandably so, knowing that $\Delta p$ is proportional to $L_\omega$ (equation 4.1).

Table 1: Cut Off Frequencies & Pressure Drop for Different Attenuator Lengths

<table>
<thead>
<tr>
<th>$L_\omega$ (mm)</th>
<th>$f_0$ (KHz)</th>
<th>$\Delta p$ mmH$_2$O</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>10</td>
<td>12.5</td>
</tr>
<tr>
<td>250</td>
<td>12.5</td>
<td>11.7</td>
</tr>
<tr>
<td>200</td>
<td>14</td>
<td>10.5</td>
</tr>
<tr>
<td>150</td>
<td>19</td>
<td>8.7</td>
</tr>
</tbody>
</table>
Fig 4.9 Changing cut-off freq. & pressure loss with filter length

Fig. 4.10 Turbulence spectrograph before filtering

Fig. 4.11 Turbulence spectrograph after filtering, $L_\omega = 250$
Figures 4.11 and 4.12 are plots of the turbulence spectrum of two of the attenuators in table 1. Case of \( L_w = 250 \text{ mm} \) (figure 4.11) and \( 300 \text{ mm} \) (figure 4.12); while figure 4.10 gives the turbulence spectrum of homogenous wind flow before the attenuator was installed.

The peaks on the graph correspond to the 12th, the 18th and the 24th harmonic of the Blade Pass Frequency-BPF - (of 560 Hz) of the centrifugal blower used. These frequencies had previously been swamped by turbulence.

The still air spectrum is the reference spectrum. It has a different level to that measured in figure 4.2. This is hardly surprising as these experiments were conducted on separate days, with each day obviously having different ambient conditions.

Note

\[ BPF = \left( \frac{N_b \times \text{RPM}}{60} \right); \quad N_b = \text{Number of blades on the impeller of centrifugal blower (}=12) \]

and \( \text{RPM} = \text{Number of rotations per minute of the impeller (}=2800\text{rpm}) \)

The filters were found to have an average wind speed of 22.5 m/s. The wind speed and pressure drop were measured using a hand held HWA model TA6000 and a Mark 4
manometer respectively, both by AIRFLOW Developments Ltd.

4.5 Acoustic Evaluation of the Turbulence Attenuator.

To appreciate the effects of the turbulence filter on the quality of organ pipe sound, it is essential to evaluate its performance both qualitatively and quantitatively as well as have an aural assessment of its effects on the musical character of the instrument.

4.5.1 A Qualitative Evaluation

Figure 4.13 portrays the schematic block diagram of the method used for this evaluation.
This technique involves recording individual notes on certain stops on the organ where the problem of flutter and ripple thought to be induced by turbulence is most prominent. These recordings were done on HHb PQ92 digital audio tapes with the help of a CASIO DA-7, digital audio tape (DAT) recorder. The recordings were taken before and after the turbulence attenuator was installed in the organ wind trunk.

Samples taken included recordings of about three dozen notes on the Gedackt 8ft, the 4ft Rohrflöte and the 2ft Principal stops.

On play back, the output of the recorder was channelled into the spectrum analyser to evaluate the characteristics of fundamental of some of the pipes.

In figures 4.14-4.27 are spectrographs of some notes before and after the attenuator was installed on the St. Paul's organ.

Fig. 4.14 - The F# on the 8ft Gedackt stop before turbulence filtering
4.15 - The F# on the 8ft Gedackt stop after turbulence filtering
4.16 - The C on the 8ft Gedackt stop before turbulence filtering
4.17 - The C on the 8ft Gedackt stop after turbulence filtering
4.18 - The E on the 8ft Gedackt stop before turbulence filtering
4.19 - The E on the 8ft Gedackt stop after turbulence filtering
4.20 - The A on the 2ft Principal stop before turbulence filtering
4.21 - The A on the 2ft Principal stop after turbulence filtering
4.22 - The C on the 2ft Principal stop before turbulence filtering
4.23 - The C on the 2ft Principal stop after turbulence filtering
4.24 - The F on the Rohrflute 4ft stop before turbulence filtering
4.25 - The F on the Rohrflute 4ft stop after turbulence filtering
4.26 - The C on the Rohrflute 4ft stop before turbulence filtering
4.27 - The C on the Rohrflute 4ft stop after turbulence filtering

(The vertical axis = magnitude; horizontal axis = frequency for figs. 4.14-4.27)
Note how the note had a spectrum with bumps and troughs as well as two peaks (at 738 Hz & 742 Hz with a difference of ~2 dB between them) before turbulence attenuation. After attenuation, the note is much smoother, i.e. it is less bumpy and has just one peak.

Some notes on figures 4.14 - 4.27

In some of the ensuing figures, serious attention should not be paid to the scales of the vertical axis. The figures should be regarded more as an illustration to aid the qualitative evaluation of the note. This is because the recordings were done on different days. In addition, the microphone position was not the same for every note or corresponding pairs of notes recorded with and without the turbulence attenuator.
Note that the peak at 610Hz has been eliminated. A rough looking note before turbulence attenuation is now much smoother apart from the much attenuated bumps in the neighbourhood of 480Hz and 560Hz.
4.18 - The $E_{29}$ note on the 8ft Gedackt stop before turbulence filtering

4.19 - The $E_{29}$ note on the 8ft Gedackt stop after turbulence filtering

The bumps between 240Hz and 260Hz have been suppressed with turbulence attenuation. Bumps at 340Hz and beyond have been significantly attenuated.
The note has a much smoother spectrum with turbulence attenuation. The peak at near 900Hz is still prominent. The peak could be a component of some resonant effect in the soundboard or a component of the Blade Pass Frequency of the fan.
Fig. 4.22 - The $C_1$ note on the 2ft Principal stop before turbulence filtering

Fig. 4.23 - The $C_1$ note on the 2ft Principal stop after turbulence filtering

The ripples on the note have been attenuated with turbulence attenuation. The peaks at 256Hz and 300Hz have also been curtailed.
The peaks at 673Hz and 688Hz have been attenuated with turbulence attenuation. The rise to and fall from the peak is gradual. There is also a decrease in the bumpiness of the note.
The peak at ~2.05kHz and 2.18kHz are still prominent, however, the spectrum of this note is much smoother.

Overall, the plots reveal much reduction in the bumps of the leading and trailing edge of the fundamentals of the notes under examination. The overall shape of the fundamental is smoother. In Chapter five it will be shown that the shift in frequency is a characteristic that comes with the change in the turbulence condition of the wind supply.

Prior to turbulence attenuation, F#43 spectrum has two peaks, the lower frequency peak has disappeared after the wind was subjected to turbulence attenuation.
4.5.2 A Quantitative Evaluation

While the plots of figures 3.11 clearly show some improvements in the sound quality, they do not however give any indication quantitatively on how much improvement have been achieved.

Having examined the statistical nature of turbulence in chapter 3, a quantification of the changes experienced by installing the turbulence filter could be done by means of statistical procedures. Further discussion of this is delayed till chapter 5, where the effects on frequency, note symmetry and peakedness would be studied.

4.5.3 An aural evaluation

At the authors request, Jarvis\textsuperscript{48} conducted a musical evaluation of some of the perceived changes in the quality of music of the St. Paul’s organ after the turbulence attenuator was installed. The improvements cited have been independently corroborated by the manufacturers of the instrument, Wood of Huddersfield.

A decrease in the non-harmonic noise of the instrument as a whole was experienced. The pipe work of the 8 ft Gedackt stop, one of the stops on which some notes on the manual were recorded - has undergone “considerable improvement” as well as a steadier pitch. Some of the pipes still exhibit unsteadiness, however, this is more likely due to the non-harmonic noise generated by the pipework after the filter.

On other stops where the influence of the turbulence was thought not to be too significant, there has also been some notable improvements. Amongst these stops are the 16ft Gedackt Pommer, 4ft Spitzflöte, 8ft Principal (manual 2), the Cromhorne (manual 1), 2ft Flute (manual 3); the 16ft and 8ft Principal, 16ft Sub-bass and Reeds (all pedal). There has also
been considerable improvement to the 16ft and 8ft Trumpets (manual 2).

The 16ft Gedackt Pommer (manual 2) has lost its “acidity ... in the treble registers”. It also blends in much better with the pipework in that division. The 4ft Spitzflote and the 8ft Principal (manual 2) speak much more clearly, as well as the Reeds, which have a “more penetrating tone.”

The pedal stops have generally undergone an improvement in tonal quality. They now exhibit a greater depth and steadiness of tone.

The 8ft flute and the 2ft Blockflöte (manual 3) are less shrill: furthermore the pipework of these stops now have a much better blend.

In all, Jarvis adds that there is a “pronounced degree of articulation from the instrument [along with a greater possibility] to control the speech of the pipes to a much greater degree of accuracy”.

These improvements clearly augment the expressiveness of the St. Paul’s Organ.

4.6 Use of Centrifugal Fan at off Optimum Design Condition as means of Minimizing Turbulence

A turbulence filter was also installed on the trunking system of an organ built by Harrison & Harrison (Durham -UK) destined for USA, while it was being erected at their workshop. A Centrifugal blower (1425 rpm, 1.125 kW -1.5hp- 12 paddle/radial blades) was used for supplying wind to the organ. It turned out that the filter did not produce any perceivable improvements. It was speculated that the machine maybe unexpectedly producing near laminar wind by feeling the wind flow emanating from it. Tests had to be conducted to confirm this.

The blower was tested in Huddersfield.
The flow from the blower was varied between ~0% and 100% output by blocking the outlet of a duct with orifice plates. The diameters of the orifices were not more than the duct diameter. The power consumption of the motor driving the blower was measured as the flow was varied. From these, the power (as well as head and efficiency) versus flow rate curves were plotted to determine the optimum operating point of the centrifugal blower. The curves are as in figure 4.28 and 4.29 below.

The blower was delivering wind into the organ destined for USA, to a pressure of 6.4mbar (ie 2.5inches H₂O). From the curves of figure 4.28 and 4.29, this corresponds to an efficiency of 26% and a power consumption of 914.5 Watts.

![Fig 4.28 Head, Power & Efficiency vs flow rate for Harrison Centrifugal Blower (before turbulence filter installed)](image)
These parameters are below the optimum operating point (>33% efficiency) of the blower. It is possible that the relative absence of turbulence in the centrifugal blower could be because it is operating below optimum efficiency.
CHAPTER 5

AN EVALUATION OF THE EFFECTS OF TURBULENCE ATTENUATION.

5.1 Introduction

One of the questions this research aims to answer is whether organ pipe sound changes with varying degrees of turbulence. Furthermore, whether these changes are aurally perceivable. To answer these questions some qualitative analysis was conducted with sound from the St. Pauls Organ (reported in section 5.4) and later from a laboratory test rig (reported in section 5.5). Remarks were solicited from individuals and members of an audience after they had listened to the pipes blown with filtered and unfiltered wind. It was noted that the pipes on the test rig were “noticeably clearer” with turbulence attenuation as will be discussed in section 5.3.

An experiment was conducted on a test rig that had 4 Principal pipes of various frequencies. Wind with five different mixtures of turbulent to laminar flow was pumped into the windchest (soundboard) holding the pipes. Over three dozen students were used as guinea pigs in a blind test to evaluate the sound produced. This experiment was conducted to establish whether varying the levels of turbulence of wind into the pipe is perceivable and whether there is a threshold of turbulence in the wind that is acceptable. In section 5.3.2, more details on this experiment and results will be given.

Aural perception of changes in sound is largely subjective because the frequency response of the ear varies from person to person. It is essential therefore to seek to quantify the changes in the note as the flow condition changes. To achieve this, statistical principles
were used. The statistical concept used are derived from the concept of moments. The 3rd and 4th moments about a reference point were used to determine changes in skewness and peakedness/kurtosis of the note. The mathematical procedure used is discussed in appendix 7 while the results of the qualitative evaluation are outlined in section 5.5 for data from St. Paul’s and the test rig.

Each pipe produces sound consisting of its fundamental and harmonics. When a pipe is said to have a frequency, f_p, f_p is the fundamental - therefore it is the fundamental that defines the frequency of a pipe not its harmonics, hence the quantitative evaluations carried out in the ensuing sections were with the fundamental only.

It was noted that changing the levels of the turbulence causes a frequency shift in the note. These observations are also outlined in this chapter (section 5.5.2 and 5.5.1 for data from St Paul’s and the test rig respectively)

In the organ building trade, there is a strong perception that organs that use human operated blowers provide a superior wind supply relative to fans and other wind machinery in use. A quantitative analysis was conducted on notes recorded from an organ in a local church that has a dual blowing system, a centrifugal fan and a manually operated bellows. Some notes were recorded when the organ was fed wind from either blowing systems for a comparative analysis. The details of this analysis is also given in this chapter in section 5.7.

Before embarking on a discussion of the aural evaluation of data from St. Paul’s and the lab test rig, an outline of the test rig used will be given.
5.2 Evaluation of data from test rig

A laboratory test rig was designed and built to evaluate the effects of different levels of turbulence on the quality of sound.

The aims of the experiments were:
- To numerically evaluate the effects of changing the level of turbulence,
- To ascertain whether the effects of turbulence are aurally perceivable;
- To find out whether there is a threshold of turbulence at which the effects of turbulence on the quality of organ pipe sound can be tolerated.

5.2.1 Test rig design.

Figure 5.1 (overleaf) is an illustration of the test rig used for this exercise.
Chapter 5: An Evaluation of the Effects of Turbulence Attenuation

Fig. 5.1 Sketch of experimental rig

TOP VIEW
windchest

Organ Pipes

Opening for pressure measurements

Turbulence filter

Side view of windchest with pipes

V1
V2

A1
A2

Input from blower

V3
5.2.1.1 The test rig.

Wind from a fan (not shown) is blown in to the system via a reservoir (not shown) from where it flows downstream into the test rig. Some of the wind is leaked through valve V3, to provide the design pressure (6.4 mbar - 2.5 inches H₂O) of the pipes on the windchest.

The wind into the system flows through arms A1 and A2 downstream into the windchest. Wind flowing down arm A1 flows through the turbulence attenuator, while that through A2 does not. The wind through A1 and A2 meet at a confluence before flowing downstream into the windchest.

The attenuator used in the test rig was designed such that it was geometrically similar to that built for St. Paul's. The dimensions of the duct to which the filter was connected was 80mm by 80mm. The duct was gradually expanded to 200mm by 200mm to accommodate the filter. The reader should recall that the filter is made up of narrower channels, whose total cross sectional area equals the area of the duct. However, because of the finite thickness of the walls of the narrow channels, the total area they take up is more than the area of the duct.

Orifice plates V1 (of arm A1) and V2 (of arm A2) are used to control the mixture of wind flowing into the windchest/soundboard. When V1 is fully open and V2 closed, the turbulence of the wind flowing into the windchest is attenuated. When V2 is open and V1 is closed, the wind flowing into the windchest is turbulent. When V1 and V2 are both half open, the wind mixture is 50% turbulent attenuated and 50% turbulent and so on for V1 25% open and V2 75% open; and V1 75% open and V2 25% open. V1 and V2 were operated such that the sum of turbulent attenuated and turbulent wind flowing into the windchest was (ideally) always 100% as per table 2.
The pipes, Pipe 1 to Pipe 4 sit on the windchest. Four switches open or close the inlet into the toe hole to each pipe. When switch one is open, air flows into the toe hole of Pipe 1 to produce sound. Pipes 2, 3 and 4 can be similarly switched on.

The switches were energized from a Farnell E30/2 power supply. The switches controlled a the solenoid magnet that closed and opened the pallet at the foot of the pipe. An opened pallet allowed wind to flow into the pipe and vice versa for the closed pallet.

The bifurcating Y junction before V1 and V2 and converging Y junction after, were designed such that their angle of separation was small enough to minimise boundary layer separation.

On the windchest were four flue pipes, with the following frequencies: Pipe 1, 260Hz; Pipe 2; 520Hz; Pipe 3, 1078 Hz and Pipe 4 2084 Hz.

The windchest was built to the following internal dimensions: length 300mm, width 150mm, and height 150mm.

Each pipe was played under the five different flow conditions of table 2, above, and the sound recorded on a DAT recorder.
The wind into the system was provided by a DISCUS centrifugal blower, propelled by a Brook Crompton 250W motor, running at 2850 rpm; with an output pressure of \( \sim 560 \text{Pa}(2.25 \text{ inches H}_2\text{O}) \)

5.3 An aural assessment of the tones from test rig

5.3.1. An assessment via individual remarks

About a dozen students taking organ studies as their main option within the Music Department of the University were invited to listen to the four pipes on the windchest of the test rig under two flow conditions: 100% turbulence and 100% lamina flow. They were invited to write a brief report on what they heard for the different blowing conditions. Some of the remarks they made are given below.

-1- "There was a marked difference in the turbulence free pipe sounds in that it was a generally cleaner, more pure sound. However this was only really noticeable in the lower registers..."

-2- "A slight difference in sound can be detected by ear in lower frequency pipes."

-3- "With the high-pitched pipes it was not possible to hear an audible difference, though a slight difference was heard when the largest pipe was used. The filtered wind gave the pipe a smoother speech quality."

-4- "It was easy to detect the improvement of sound with filtered wind compared with turbulent wind, with the lower frequencies, but no change was detectable with the higher frequencies."
-5- "...the sound heard with the presence of the air filter was more pure, it was closer to the center of the particular pitch ... The difference in sound was noticeably clearer ..."

-6- "...without a filter, you are able to hear an unevenness of tone as the note wavers. This is more apparent in the lower registers. ...with a filter the notes are more stable."

-7- "...it was the two higher pitched pipes which sounded better on filtered air ... the lower pitched pipes produced a barely obvious difference."

-8- "...the experiment proved to me that there is a difference to sound quality with the use of filtered wind, but I think the difference is appreciated at lower pitches."

-9- "... [the] lower sounding pipes were clearer with more 'bite' to the sound. Higher sounding [frequency] notes were not heard so much ..."

-10- "Even though the difference to me was slight on one note, I can imagine that on a large scale (full organ) the difference is quite considerable."

These remarks suggest that the changes in tone due to changing wind flow conditions are perceivable. The changes seem to be more perceivable for the lower registers (pitches).
5.3.2. An assessment via questionnaire

For each of the different flow conditions, each pipe was switched on to an audience of music students from the Department of Music of the University. The students were asked to give a subjective appreciation of the tone produced by the pipe. To assist the students in their response, each of them was given a questionnaire - reproduced in appendix 6. About 40 students took part in the exercise. Their responses are tabulated in table 3 overleaf, with corresponding bar charts in figure 5.2.

A clear pattern emerged from table 6 overleaf. The tone changes with changing levels of turbulence is aurally perceivable. However, there is no clear distinction as to which turbulence condition is the most preferred - which comes as no surprise as each person's ear has his/her own particular frequency response. As such, the judgement of each 'guinea pig' remains wholly subjective.

Consider row 6, containing results for 50% laminar flow. For pipe 1, none in the audience thought the note was poor. About 3% felt the note was poor; a similar percentage perceived the note as brilliant for this flow mixture. 51% perceived the note to be good, while 43% thought the note was better.

For Pipe 2, the story is different: 54% judged the note was poor, 3% thought the note was poor, while 35% judged it to be good. Only 8% judged the note to be better, while 35% thought the note was good.

Pipe 3 attracted responses dissimilar to those of pipes 1 and 2. About 38% of the audience felt the note was better with this wind mixture. 19% judged the note to be poor; a similar percentage perceived the note to be good. Under 25% of the audience judged that the note had become horrible.
<table>
<thead>
<tr>
<th>Flow Condition</th>
<th>Pipe 1</th>
<th>Pipe 2</th>
<th>Pipe 3</th>
<th>Pipe 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Lamina)</td>
<td>Audience Response(%)</td>
<td>Audience Response(%)</td>
<td>Audience Response(%)</td>
<td>Audience Response(%)</td>
</tr>
<tr>
<td>100</td>
<td>2.7</td>
<td>59.5</td>
<td>24.3</td>
<td>5.4</td>
</tr>
<tr>
<td>75</td>
<td>0</td>
<td>28.6</td>
<td>21.4</td>
<td>42.9</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
<td>2.7</td>
<td>51.4</td>
<td>43.2</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>13.5</td>
<td>46.0</td>
<td>40.5</td>
</tr>
</tbody>
</table>

(1 = Horrible, 2 = Poor, 3 = Okay, 4 = Good, 5 = Brilliant)

Table 5 Audience response to questions in questionnaire of appendix 8
Figure 5.2 Charts of audience response for different pipes

5 = Brilliant, 4 = Good, 3 = Okay, 2 = Bad, 1 = Horrible
For pipe four: over 5% of the audience felt the note had become brilliant, while 11% judged it to be horrible. 32% thought the note was poor and 14% thought it was better, while 38% judged the note to be good.

Additional analysis can be undertaken with the charts of figure 5.2. Consider the percentage of respondents who expressed an opinion that the sound was "Good" - 4- or "Brilliant" -5-. For pipe 1, the largest percentage of Good & Brilliant responses combined was for the case of 75% turbulence attenuated (or 25% turbulent) flow, closely followed by 50% laminar (50% turbulent) flow. In the case of pipe 2, 75% & 0% turbulent attenuated flow provided the largest percentage of Good & Brilliant responses combined. For pipe 3, the largest percentage of Good & Brilliant responses combined was the situation of no turbulence attenuation, closely followed by 50% turbulence attenuated flow. For pipe 4, the largest percentage of Good & Brilliant responses combined was the situation of no turbulence attenuation followed by 75% turbulence attenuated flow.

We see that for each pipe, we get a different response from the audience for the same flow condition. The different percentages that indicate the appreciation of the audience of a pipe tone under different flow conditions, confirm that changing the turbulence level produces perceivable changes in the tonal quality.

The figures also indicate that it is probably not possible to determine an acceptable threshold of turbulence in organ wind supply, because musical appreciation is primarily subjective. However analysis from the chats using “Good” and “Brilliant” responses seem to indicate that turbulent attenuated wind is the preferred or next best option.

Having carried out a qualitative analysis of the effects of turbulence, a quantitative analysis was also undertaken. The method of analysis applied the principles of statistical moments. A derivation of the mathematical technique is outlined in appendix 7.
ensuing sections, the results from the calculations of data from St Paul's and the test rig are discussed.

5.4 An aural evaluation of St. Paul's Data

At the authors request, Jarvis, conducted a musical evaluation of some of the perceived changes in the quality of music of the St. Paul's organ after the turbulence attenuator was installed. The improvements cited have been independently corroborated by the manufacturers of the instrument, Wood of Huddersfield.

A decrease in the non-harmonic noise of the instrument as a whole was experienced. The pipe work of the 8 ft Gedackt stop, one of the stops on which some notes on the manual were recorded - has undergone “considerable improvement” as well as a steadier pitch. Some of the pipes still exhibit unsteadiness, however, this is more likely due to the non-harmonic noise generated by the pipework after the filter.

On other stops where the influence of the turbulence was thought not to be too significant, there has also been some notable improvements. Amongst these stops are the 16ft Gedackt Pommer, 4ft Spitzflöte, 8ft Principal (manual 2), the Cromhorne (manual 1), 2ft Flute (manual 3); the 16ft and 8ft Principal, 16ft Sub-bass and Reeds (all pedal). There has also been considerable improvement to the 16ft and 8ft Trumpets (manual 2).

The 16ft Gedackt Pommer (manual 2) has lost its “acidity ... in the treble registers”. It also blends in much better with the pipework in that division. The 4ft Spitzflote and the 8ft Principal (manual 2) speak much more clearly, as well as the Reeds, which have a “more penetrating tone.”

The pedal stops have generally undergone an improvement in tonal quality. They now exhibit a greater depth and steadiness of tone.
The 8ft flute and the 2ft Blockflöte (manual 3) are less shrill; furthermore the pipework of these stops now have a much better blend.

It was also observed that there is a "pronounced increase in the degree of articulation from the instrument [along with a greater possibility] to control the speech of the pipes to a much greater degree of accuracy". These improvements clearly augment the expressiveness of the St. Paul's Organ.

5.5 Quantitative Evaluation of Pipe Data

Data collected from both the test rig and St Paul’s were quantified using the concept of statistical moments as outlined in appendix 7. The 3rd moments which measured the change in skewness of the data and the 4th moment which gave a measure of the "peakedness" of the note were calculated. The results outlined in the rest of section 5.5 are from the test rig data and St. Paul’s respectively.

5.5.1 Evaluation of moment of data from test rig

The recordings of the notes taken under different flow conditions were played back into the B&K spectrum analyser and their fundamentals sampled (as earlier described in appendix 7) for analysis.

The 3rd and 4th moments were computed using the statistical software package MINITAB. The flow chart of the programme used is as in appendix 8a. The moments calculated are given in the next two.

5.5.1.1 Third moments of test rig data

Table 4 below contains the 3rd moments of the different pipes under different flow
conditions.

Table 4: Data Table of Skewness with Increasing Laminar Flow

<table>
<thead>
<tr>
<th>Flow Condition (lamina) %</th>
<th>Pipe 1 (P1)</th>
<th>Pipe 2 (P2)</th>
<th>Pipe 3 (P3)</th>
<th>Pipe 4 (P4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-0.4498</td>
<td>-0.4317</td>
<td>-0.2976</td>
<td>-0.23223</td>
</tr>
<tr>
<td>25</td>
<td>-0.4845</td>
<td>-0.4186</td>
<td>-0.3161</td>
<td>-0.32786</td>
</tr>
<tr>
<td>50</td>
<td>-0.5161</td>
<td>-0.4362</td>
<td>-0.2684</td>
<td>-0.34267</td>
</tr>
<tr>
<td>75</td>
<td>-0.4888</td>
<td>-0.4618</td>
<td>-0.343</td>
<td>-0.3591</td>
</tr>
<tr>
<td>100</td>
<td>-0.5045</td>
<td>-0.4388</td>
<td>-0.3168</td>
<td>-0.3123</td>
</tr>
</tbody>
</table>

a. Example of sampled data from test rig is presented in appendix 8 together with the dimensions of pipes 1-4

It is evident that all the third moments are negative, further indicating that the shape of the organ pipe tone generally has negative asymmetry (skewness).

The data of table 4 was plotted. The curves in figure 5.3 depicts the behaviour of the third moment with increasing laminar flow

\[ PN = \text{Pipe N} \]

There is a pattern in the curves. The curves exhibit a non-monotonical increase in asymmetry of the shape of the pipe fundamental with increasing laminar flow.
5.5.1.2 Fourth moments of test rig data

Table 5 contains the fourth moments of the different pipes under different flow conditions.

<table>
<thead>
<tr>
<th>Flow Condition (lamina) %</th>
<th>Pipe One</th>
<th>Pipe Two</th>
<th>Pipe Three</th>
<th>Pipe Four</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.38276</td>
<td>0.36603</td>
<td>0.2382</td>
<td>0.16648</td>
</tr>
<tr>
<td>25</td>
<td>0.42306</td>
<td>0.34915</td>
<td>0.25558</td>
<td>0.25371</td>
</tr>
<tr>
<td>50</td>
<td>0.45863</td>
<td>0.36812</td>
<td>0.2069</td>
<td>0.26752</td>
</tr>
<tr>
<td>75</td>
<td>0.42487</td>
<td>0.39861</td>
<td>0.28373</td>
<td>0.28734</td>
</tr>
<tr>
<td>100</td>
<td>0.43878</td>
<td>0.41275</td>
<td>0.2557</td>
<td>0.23301</td>
</tr>
</tbody>
</table>

The data in table 5 was plotted to yield the family of curves in figure 5.4 below.

![Figure 5.4: Plots of the fourth moments vs flow for test rig data.](image)

PN = Pipe N

The curves bear some pattern. There is a non-monotonical increase in peakedness of the pipe fundamental with increasing laminar (decreasing turbulence) flow.
5.5.2 Evaluation of moments of data from St. Paul’s

The statistical software package, MINITAB was used to evaluate the moments.

5.5.2.1 Moments of St Paul’s Data

The 3rd and 4th moments were computed using the statistical software package MINITAB. The flow chart of the programme used is as in appendix 8a. The moments calculated are given in tables 6 (3rd moments) 7 (4th moments) overleaf.

<table>
<thead>
<tr>
<th>Stop</th>
<th>Notes</th>
<th>3rd Moment before filtering</th>
<th>3rd Moment after filtering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gedackt 8ft</td>
<td>E₂⁹</td>
<td>-0.3321</td>
<td>-0.4022</td>
</tr>
<tr>
<td>Gedackt 8ft</td>
<td>F♯₄₃</td>
<td>-0.3262</td>
<td>-0.3212</td>
</tr>
<tr>
<td>Gedackt 8ft</td>
<td>A₄⁷</td>
<td>-0.393</td>
<td>-0.326</td>
</tr>
<tr>
<td>Gedackt 8ft</td>
<td>G₅₆</td>
<td>-0.4107</td>
<td>-0.2997</td>
</tr>
<tr>
<td>Gedackt 8ft</td>
<td>C₆₁</td>
<td>-0.2778</td>
<td>-0.2925</td>
</tr>
<tr>
<td>Principal 2ft</td>
<td>A♯₂₃</td>
<td>-0.3396</td>
<td>-0.4395</td>
</tr>
<tr>
<td>Principal 2ft</td>
<td>C₁</td>
<td>-0.4527</td>
<td>-0.5351</td>
</tr>
<tr>
<td>Principal 2ft</td>
<td>F₁₈</td>
<td>-0.3661</td>
<td>-0.3806</td>
</tr>
<tr>
<td>Rohrflute 4ft</td>
<td>B₁₂</td>
<td>-0.3813</td>
<td>-0.4211</td>
</tr>
<tr>
<td>Rohrflute 4ft</td>
<td>C♯₅₀</td>
<td>-0.2017</td>
<td>-0.3547</td>
</tr>
<tr>
<td>Rohrflute 4ft</td>
<td>F₃₀</td>
<td>-0.3724</td>
<td>-0.4269</td>
</tr>
</tbody>
</table>

It is clear that the 3rd moments of all the notes are negative, suggesting that the natural state of the note is one of negative skewness or negative asymmetry. Of the eleven notes analysed, eight have become more negatively asymmetrical (in bold) after turbulence
Chapter 5: An Evaluation of the Effects of Turbulence Attenuation

attenuation: suggesting that the lower the amount of turbulence in the flow, the more negative is the asymmetry within the note.

Turbulence tends to even things out. The tendency for a tone to become more symmetrical when generated by turbulent wind could be due to the "evening out" process.

For instance, if milk were poured into the centre of a still cup of tea, the tea principally stays dark, with a white central area: stirring the tea, i.e., introducing turbulence in the tea, spreads the milk evenly within the tea.

It is likely that turbulence in wind supplied to an organ, also evens out the tone - aspiring to give it symmetry about the centre frequency.

Table 7 below contains the calculations of the fourth moment.

<table>
<thead>
<tr>
<th>Stop</th>
<th>Notes</th>
<th>4th Moment before filtering</th>
<th>4th Moment after filtering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gedackt 8ft</td>
<td>E₂₉</td>
<td>0.258</td>
<td>0.3243</td>
</tr>
<tr>
<td>Gedackt 8ft</td>
<td>F₅₃</td>
<td>0.2596</td>
<td>0.2539</td>
</tr>
<tr>
<td>Gedackt 8ft</td>
<td>A₇₇</td>
<td>0.3166</td>
<td>0.2499</td>
</tr>
<tr>
<td>Gedackt 8ft</td>
<td>G₅₆</td>
<td>0.3366</td>
<td>0.2319</td>
</tr>
<tr>
<td>Gedackt 8ft</td>
<td>C₆₁</td>
<td>0.2166</td>
<td>0.2271</td>
</tr>
<tr>
<td>Principal 2ft</td>
<td>A₂₃</td>
<td>0.2549</td>
<td>0.359</td>
</tr>
<tr>
<td>Principal 2ft</td>
<td>C₁</td>
<td>0.3762</td>
<td>0.468</td>
</tr>
<tr>
<td>Principal 2ft</td>
<td>F₁₈</td>
<td>0.2891</td>
<td>0.3036</td>
</tr>
<tr>
<td>Rohrflute 4ft</td>
<td>B₁₂</td>
<td>0.3075</td>
<td>0.3529</td>
</tr>
<tr>
<td>Rohrflute 4ft</td>
<td>C₇₅₀</td>
<td>0.1464</td>
<td>0.3032</td>
</tr>
<tr>
<td>Rohrflute 4ft</td>
<td>F₃₀</td>
<td>0.3044</td>
<td>0.3553</td>
</tr>
</tbody>
</table>

It is realised here that the 4th moments generally increase after turbulence attenuation - suggesting an increase in the peakedness of the note. Eight of the eleven notes studied
have peaked more with the turbulence attenuator in place. This can be associated with the improved brightness\textsuperscript{48} and “more bite” [See remarks section 5.3.1] encountered.

5.6 Effects of changing flow conditions on frequency

It was also noted that changing the levels of turbulence resulted in a frequency shift in the note. These effects were observed both in data from St. Paul’s and the test rig.

5.6.1 Frequency variations and Turbulence in St Paul’s Organ

The frequency of the fundamentals of some of the pipe tones were determined using the B&K spectrum analyser. It was noticed that there were changes in the value of the frequency before and after the turbulence attenuation. These changes are illustrated in table 8 below.

<table>
<thead>
<tr>
<th>Stop</th>
<th>Note</th>
<th>Frequency before $F_b$ (Hz)</th>
<th>Frequency after $F_a$ (Hz)</th>
<th>Frequency change $F_a-F_b$ (Hz) - (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rohrflute 4ft</td>
<td>B\textsubscript{12}</td>
<td>246.625</td>
<td>246.125</td>
<td>-0.5 (0.2%)</td>
</tr>
<tr>
<td>Principal 2ft</td>
<td>C\textsubscript{1}</td>
<td>260.75</td>
<td>261</td>
<td>+0.25 (0.1%)</td>
</tr>
<tr>
<td>Gedackt 8ft</td>
<td>E\textsubscript{29}</td>
<td>329.75</td>
<td>328.5</td>
<td>-1.25 (0.4%)</td>
</tr>
<tr>
<td>Rohrflute 4ft</td>
<td>F\textsubscript{30}</td>
<td>698.5</td>
<td>696.625</td>
<td>-1.875 (0.3%)</td>
</tr>
<tr>
<td>Gedackt 8ft</td>
<td>F#\textsubscript{43}</td>
<td>740.625</td>
<td>738.25</td>
<td>-2.375 (0.32%)</td>
</tr>
<tr>
<td>Principal 2ft</td>
<td>A#\textsubscript{23}</td>
<td>929</td>
<td>929.5</td>
<td>+0.5 (0.05%)</td>
</tr>
<tr>
<td>Gedackt 8ft</td>
<td>A#\textsubscript{47}</td>
<td>932.875</td>
<td>929.75</td>
<td>-3.125 (0.34%)</td>
</tr>
<tr>
<td>Rohrflute 4ft</td>
<td>D#\textsubscript{40}</td>
<td>1244.375</td>
<td>1240.375</td>
<td>-4 (0.32%)</td>
</tr>
<tr>
<td>Principal 2ft</td>
<td>F\textsubscript{18}</td>
<td>1388</td>
<td>1390.5</td>
<td>+2.5 (0.2%)</td>
</tr>
<tr>
<td>Gedackt 8ft</td>
<td>G\textsubscript{56}</td>
<td>1571.375</td>
<td>1566</td>
<td>-5.125 (0.33%)</td>
</tr>
<tr>
<td>Gedackt 8ft</td>
<td>C\textsubscript{61}</td>
<td>2096.625</td>
<td>2089.375</td>
<td>-7.25 (0.35%)</td>
</tr>
<tr>
<td>Rohrflute 4ft</td>
<td>C#\textsubscript{50}</td>
<td>2219.25</td>
<td>2211.875</td>
<td>-7.375 (0.33%)</td>
</tr>
</tbody>
</table>
Table 8 shows a general decrease in the magnitude of the centre frequency: 75% of the notes have experienced a decrease. In musical terms, this is equivalent to a flattening of the note. The flatness observed in table 8, coincides with perceptions from aural evaluation.48

It is observed that only the Principals have gone sharper while the flutes have become flatter. The principals, unlike the other pipes, were nicked. Their behaviour, though out of pattern with those of the other pipes, is a characteristic of nicked pipes as shall be discussed later in section 5.6.2.

It will seem that the frequency shifts increase with increasing pipe frequency, however as a percentage, the shifts are broadly the same, ≈ 0.3% shifts. The percentage change may look small, however, the changes are perceivable. Experiments conducted by Gueritey39, has shown that a pressure drop of 10% in an organ system caused a frequency shift in the “D-major chord” of the St. Jean de Losne organ, in France, from 1064Hz to 1058Hz. A shift of 6Hz or 0.56%, which Gueritey described as “fully perceptible to the ear!”39

5.6.2 Frequency variations and Turbulence in Test Rig

Measurements of the centre frequency of the note, taken on the spectrum analyser showed some variation. The centre frequency was found to shift with changing flow conditions. Table 9 below contains the frequency shifts measured.
Table 9: Measured Frequency Shifts

<table>
<thead>
<tr>
<th>Flow Condition (lamina) %</th>
<th>Pipe 1</th>
<th>Pipe 2</th>
<th>Pipe 3</th>
<th>Pipe 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe Frequencies at Full Turbulence Flow</td>
<td>260.5 Hz</td>
<td>520.3 Hz</td>
<td>1078.8 Hz</td>
<td>2084.5 Hz</td>
</tr>
<tr>
<td>Freq Shift (Hz)</td>
<td>Freq Shift (Hz)</td>
<td>Freq Shift (Hz)</td>
<td>Freq Shift (Hz)</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>0.062</td>
<td>-0.062</td>
<td>0.063</td>
<td>3.5</td>
</tr>
<tr>
<td>50</td>
<td>0.125</td>
<td>0</td>
<td>-0.125</td>
<td>4.5</td>
</tr>
<tr>
<td>75</td>
<td>0.125</td>
<td>0</td>
<td>0.25</td>
<td>1</td>
</tr>
<tr>
<td>100</td>
<td>0.187</td>
<td>0.125</td>
<td>0.5</td>
<td>6</td>
</tr>
</tbody>
</table>

From table 9, it is observed that there is an increase in frequency with increasing laminar flow condition. This frequency shift was normalised to enable the appreciation of the changes taking place.

The normalised value of the frequency shift, $\Delta f$, was obtained using equation 5.12 below:

$$\Delta f = \frac{F_p - F_{100T}}{F_{100T}} \tag{5.12}$$

where $F_p$ is the pipe frequency for a given flow condition, and $F_{100T}$ is the pipe frequency, when the wind is unfiltered - 100% turbulence flow.

Ordinarily, a blower would have been used to supply air into the organ without a turbulence attenuator, hence it was appropriate to use the pipe frequency generated by unfiltered wind as a frame of reference.
Using equation 5.12, the data of table 10 below was computed from table 9. Table 10 therefore contains the normalised frequency shift experienced under different flow conditions.

Table 10: Normalised Frequency Shifts with Changing Flow Conditions

<table>
<thead>
<tr>
<th>Flow Condition (lamina) %</th>
<th>Pipe 1</th>
<th>Pipe 2</th>
<th>Pipe 3</th>
<th>Pipe 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Δf (x 10^-4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>2.38</td>
<td>-1.192</td>
<td>0.584</td>
<td>16.79</td>
</tr>
<tr>
<td>50</td>
<td>4.798</td>
<td>0</td>
<td>-1.16</td>
<td>21.59</td>
</tr>
<tr>
<td>75</td>
<td>4.798</td>
<td>0</td>
<td>2.317</td>
<td>4.797</td>
</tr>
<tr>
<td>100</td>
<td>7.179</td>
<td>2.4</td>
<td>4.635</td>
<td>28.78</td>
</tr>
</tbody>
</table>

The normalised frequency shifts were plotted as in figure 5.5. The horizontal axis represents the change in laminar flow condition. The vertical axis represents the normalised value of the frequency change.

\[ PN = \text{Pipe } N \]

Fig. 5.5: Δf vs flow condition
Chapter 5: An Evaluation of the Effects of Turbulence Attenuation

The curves confirm that the pipe note has expressed a positive (upward) shift in frequency, with increasing laminar flow. The pipe note has grown sharper with increasing laminar (decreasing turbulent) flow.

It is also observed that the higher the pipe frequency, the greater the frequency shift.

This is unlike the observation experienced with the data from St. Paul’s.

All the pipes on the test rig had nicked languids (cf. figure 5.6). Nicked pipes behave differently from non-nicked pipes. Fletcher and Rossing,\(^{35}\) reported that nicking introduces “homogeneous turbulence” in the jet emanating from the windway. This turbulence, in the pipe mouth area, may be contributing to the sharpening of the note. If less turbulent wind flattens the note, it would be reasonable to assume that more turbulent wind would sharpen it.

\[\text{Nicks on a pipe languid}\]

\[\text{Fig. 5.6 Pipe languid with nicking}\]

5.7 Comparison between the Human Blower and Centrifugal Blower.

There is a strong perception amongst organists and organ builders that organs that use human operated blowers provide a superior wind supply relative to fans and other wind machinery in use. To establish whether this is the case, it is useful to do a comparative
analysis on some notes played under both blowing systems.

Amongst the organs visited as part of this project was the organ of St. Thomas’ Church, Thurstonland, West Yorkshire, UK. The organ here has two types of blowers, a hand operated blower and a centrifugal fan. During a trip to the Church, two notes of the organ; C25 and G32 were played on different stops and recorded. Recordings were made under both blowing situations: centrifugal blowing and hand blowing. The 3rd and 4th moments of five of the notes were evaluated for both types of blowing processes; the following results were obtained.

5.7.1 Third moments

<table>
<thead>
<tr>
<th>Stops</th>
<th>C25</th>
<th>G32</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Centrifugal Blowing</td>
<td>Hand Blowing</td>
</tr>
<tr>
<td></td>
<td>3rd Moment</td>
<td>3rd Moment</td>
</tr>
<tr>
<td>Clarabella</td>
<td>-0.373029</td>
<td>-0.360975</td>
</tr>
<tr>
<td>Clear flute</td>
<td>-0.353894</td>
<td>-0.393398</td>
</tr>
<tr>
<td>Bourdon</td>
<td>-0.469239</td>
<td>-0.422367</td>
</tr>
<tr>
<td>Flageolet</td>
<td>-0.386599</td>
<td>-0.343035</td>
</tr>
<tr>
<td>Oboe</td>
<td>-0.418355</td>
<td>-0.460199</td>
</tr>
<tr>
<td></td>
<td>-0.455812</td>
<td>-0.373340</td>
</tr>
<tr>
<td></td>
<td>-0.447778</td>
<td>-0.399334</td>
</tr>
<tr>
<td></td>
<td>-0.473469</td>
<td>-0.291883</td>
</tr>
<tr>
<td></td>
<td>-0.386631</td>
<td>-0.312154</td>
</tr>
<tr>
<td></td>
<td>-0.473616</td>
<td>-0.559633</td>
</tr>
</tbody>
</table>
It was also observed that the 3rd moments here are all negative.

Most of the third moments have become more negative with hand blowing. It has been reported that hand blowing generally produced less turbulent wind.\textsuperscript{102} The increase in negative asymmetry, ties in with previous results for air flow that underwent turbulence attenuation.

5.7.2 Fourth moments

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
 & C_{25} & \\
\hline
 & Centrifugal Blowing & Hand Blowing \\
\hline
Stops & 4th Moment & 4th Moment \\
\hline
Clarabella & 0.297336 & 0.391654 \\
Clear Flute & 0.287781 & 0.381484 \\
Bourdon & 0.401227 & 0.407070 \\
Flageolet & 0.319795 & 0.320191 \\
Oboe & 0.350667 & 0.384380 \\
\hline
G_{32} & & \\
\hline
Clarabella & 0.287940 & 0.299676 \\
Clear Flute & 0.322797 & 0.329257 \\
Bourdon & 0.356184 & 0.224966 \\
Flageolet & 0.287144 & 0.248795 \\
Oboe & 0.395498 & 0.488303 \\
\hline
\end{tabular}
\caption{4th Moments - Human vs Centrifugal Blowing}
\end{table}

The fourth moments have largely increased from centrifugal blowing to hand blowing. This increment ties in with previous results for air flow that underwent turbulence attenuation.
5.7.3 Frequency variations

The center frequency of the pipes analysed manifest a shift in frequency. The ensuing table depicts the frequency changes measured.

Table 13: Frequency Shifts from Human to Centrifugal Blowing

<table>
<thead>
<tr>
<th>STOPS</th>
<th>$C_{25}$ Frequency -Hz</th>
<th>$C_{25}$ Frequency -Hz</th>
<th>$G_{32}$ Frequency -Hz</th>
<th>$G_{32}$ Frequency -Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Centrifugal Blower</td>
<td>Hand Blower</td>
<td>Centrifugal Blower</td>
<td>Hand Blower</td>
</tr>
<tr>
<td>Clarabella</td>
<td>260.062</td>
<td>260.187</td>
<td>390.625</td>
<td>390.937</td>
</tr>
<tr>
<td>Clear Flute</td>
<td>130.062</td>
<td>130.187</td>
<td>781.250</td>
<td>781.875</td>
</tr>
<tr>
<td>Bourdon</td>
<td>520.812</td>
<td>520.812</td>
<td>194.875</td>
<td>194.937</td>
</tr>
<tr>
<td>Flageolet</td>
<td>1040.937</td>
<td>1041.5</td>
<td>1562.75</td>
<td>1564.625</td>
</tr>
<tr>
<td>Oboe</td>
<td>779.5</td>
<td>780.25</td>
<td>777.25</td>
<td>777.437</td>
</tr>
</tbody>
</table>

The fundamentals have shifted to the right (increased) with hand blowing - i.e. the pipe tones have become slightly sharper. Attention should be drawn to the fact that all the pipes on this organ [Thurstonland Organ] are nicked.

The results here mentioned follow a similar trend to the nicked pipes of the test rig.

The differences in tonal quality for pipes that have wind fed directly from a fan and that supplied via a turbulence attenuator are similar to the differences between fan wind and wind supplied by hand blowing via feeders. The turbulence filter will therefore enable a quality of wind to be fed to an organ similar to that produced by hand blown feeders, thus enabling organ builders to recreate the highly admired qualities of instruments pre-1900 in modern instruments.
6.1 Electrical Analogues of Mechanical Elements.

Electrical analogues circuits have been used to study the production of sound in several tubular musical wind instruments by many researchers including: Yoshikawa & Saneyoshi, Coltman, Nolle and Finch, Caddy and Pollard, Finch and Nolle, and Elder. These instruments are made of several constituent parts. Morse argues that when the constituent parts of these musical instruments are longer than the wavelength of the sound they produce, the instrument can be modelled in electrical terms as a transmission line. When the elements of the instrument are shorter relative to the sound wavelength it produces, the instrument can be modeled as an electrical circuit with lumped elements such as Resistance, Capacitance and Inductance. An explanation as to how the lumped circuit components are determined will be given later.

In the model developed in this research the air supply portion and part of the generator have been reduced to a driving potential (or electromotive force) into the equivalent circuit. The resonator or resonance portion of the pipe is conceptually split into several interconnected entities: the mouth (M) and input segment (I), oscillator (O) and oscillator-air interface (A).

\[ \text{Sound Generator Portion} \]
\[ \text{Resonance Column/Portion} \]

\[ M \quad I \quad O \quad A \]

Figure 6.0: Basic Configuration of Pipe
6.1.1 Impedance

The acoustic impedance of sound vibrations is analogous to electrical impedance of an AC circuit since sound vibrations alternate like AC currents.\[50, 87\]

The acoustic impedance is defined as the excess pressure divided by volume rate of flow in the direction of propagation.\[32, 50, 63, 87\] Pressure is analogous to the electromotive force (emf) and the volume rate of flow is analogous to the electrical current.

The units of measurement of volume flow rate and pressure are customarily taken to be in cubic centimeters per second (cc/s) and in grams per centimeter per second squared (g cm\(^{-1}\) s\(^{-2}\)) respectively.

The equivalent electrical impedance is also given by the specific acoustic impedance divided by the cross sectional area of the pipe. The impedance is a complex quantity; the real part is the resistive component, while the imaginary part is the reactive component.

6.1.2 Capacitance

The capacitance is that characteristic which resists any change in applied pressure on an acoustic system.

In electrical terms,

\[\text{Capacitance, } C = \frac{Q_e}{V_e}; \quad 6.1\]

where \(Q_e\) = charge and \(V_e\) = emf or voltage(potential) difference across the capacitance plates.

The electrical charge, \(Q_e\) is given by the equation.
\[ Q_e = \int I \, dt \] \hspace{1cm} 6.2

where \( I \) is the electrical current.

In acoustic terms, the charge will be the volume displacement, in a tank say. This follows from the knowledge that the volumetric flow rate is equivalent to the electrical current. The volume displacement is usually due to a change in pressure (or voltage difference).

A capacitance is usually represented by a "buffer volume", which introduces a stiffness in a manner similar to a spring.

If the pressure changes from \( P \) to \( P + \Delta p \), and the volume displacement from \( V \) to \( V + \Delta V \), then the acoustic capacitance, \( C \) will be given by;

\[ C = \frac{\Delta V}{\Delta p} \] \hspace{1cm} 6.3

The bulk modulus of a given medium, \( K \), is given by the expression:

\[ K = \text{stress/strain} = \frac{\text{pressure change}}{\text{fractional change in volume}} \]

i.e. \[ K = \frac{\Delta p}{\Delta V/V} \] \hspace{1cm} 6.4

The velocity of sound, \( c \), in a fluid is given by the equation;

\[ c = (K/\rho)^{0.5} \]
where \( \rho \) = density of the fluid.

\[
\Rightarrow c^2 = \frac{\Delta p}{\Delta V/V} \left( \frac{1}{\rho} \right)
\]

\[
= \left( \frac{V}{C} \right) \frac{1}{\rho}
\]

\[
\Rightarrow C = \frac{V}{\rho c^2}
\]

6.5

If \( V \) is in cc, \( \rho \) in g/cc and \( c \) in cm/s; then the capacitance \( C_a \) will be in cm\(^4\)s\(^{-2}\)g\(^{-1}\).

6.1.3 Inductance

The electrical inductance (inertance) is equivalent to the mechanical inerterance.\(^{87}\) The inertance resists any change in volume current in a similar manner to the way that an inductance opposes electrical current flow.

Inertance effects are usually exhibited at constrictions.\(^{63}\) At constrictions the air within is mass controlled.

If the total mass, \( m \), of air in a constriction, were subjected to an excess pressure, \( \Delta p \), then the fluid in the constriction will acquire some Kinetic Energy due to the velocity, \( X \), of the fluid. The KE can be expressed as:

\[
KE = 0.5 m X^2
\]

\[
\therefore KE = 0.5m \left( \frac{dX}{dt} \right)^2
\]
The volume displaced due to the excess pressure = \( S_p \Delta X = \Delta V \)

\[
KE = \frac{0.5m}{S_p^2} \left( \frac{dX}{dt} S_p \right)^2 \tag{6.7a}
\]

\[
KE = 0.5 \frac{m}{S_p^2} \left( \frac{d\Delta V}{dt} \right)^2 \tag{6.7b}
\]

\[
KE = 0.5M \left( \frac{d\Delta V}{dt} \right)^2 \tag{6.7c}
\]

Where the inertance, \( M \), is equal to \( m/(S_p)^2 \). The inertance is analogous to the inductance.\(^{63, 87}\)

The mass can be determined from the density, \( \rho \), using the expression;

\[
m = \rho S_p L_p
\]

substituting the above equation into the expression for inertance, we have an equivalent inductance, \( L \), given below.

\[
L = \rho S_p L_p / S_p^2 \\
L = \rho L_p / S_p
\]

\( L_p \) = pipe length \\
\( S_p \) = pipe cross sectional area

6.3 Development of Analogous Electric Circuit of Organ Pipes

The basic configuration of organ pipes is as in figure 6.1 below\(^1\). The pipe foot and languid can be represented as sound generator;\(^3\) the area around the mouth as the feedback sector\(^98\)

---

1. A detailed schematic of a organ pipe given earlier in chapter one is also repeated in appendix 10.
and the rest of the pipe as the resonator column.

![Diagram of organ pipe configuration](image)

**Fig 6.1: Basic Configuration of Organ Pipe**

As a musical wind instrument, the organ pipe can be illustrated conceptually in the block diagram of figure 6.2; after Fletcher,\(^{32,33}\) Mahu,\(^{52}\) and MacIntyre.\(^{58}\)

![Block diagram of musical wind instrument](image)

**Fig 6.2: Block Diagram of Musical Wind Instrument**

McIntyre\(^{58}\) states that the generator is a non-linear element that is both coupled to and feeds into the resonator. The resonator is made up of passive linear elements. Their idealized model was developed as part of an investigation of the time domain description of oscillation of musical instruments.
Fletcher\textsuperscript{32} also states that the resonator portion can be treated in principle as linear in behaviour, whereas the generator is non-linear. The non-linearity could be due to the coupling with the resonator.

In analyzing the generator, which in fluid dynamic terms is the jet excitation mechanism of the sound in the pipe, Fletcher\textsuperscript{32} concedes their theoretical and experimental analysis are limited to the laminar flow regime. In other words, the influence of turbulence has been ignored or excluded. The jets are turbulent. The effects of turbulence from the wind supply into this jet was not considered.

While the jet behaviour is not investigated in this work, understanding its impact on sound generation is relevant. Later, it will be shown that the input impedance experienced by the jet is useful in determining the electrical analogue of the input impedance to the electrical equivalent circuit.

6.2.1 The Pipe Input Impedance

For open pipes, Fletcher\textsuperscript{32} shows that the input impedance, $Z_{\text{in}}$, is:

$$Z_{\text{in}} = nj \left( \frac{Dc}{S_p} \right) \tan (K - jK') \text{ ........................................... 6.9}$$

$K = \text{wave propagation number} = \omega/c$; $\omega = \text{angular frequency and } c = \text{speed of sound}$

$K' = \text{loss parameter of } K$; $j$ is the square root of minus one.

$K'$ is proportional to the square root of the angular frequency.

In arriving equation 6.9, Fletcher\textsuperscript{32} assumes free air propagation conditions and negligible energy loss at the open end (i.e. $\lambda$ (wavelength) $\gg$ pipe circumference).
Yoshikawa and Saneyoshi\textsuperscript{98} derived an expression for the input impedance, \( Z_{in} \), of an open pipe as in equation 6.10 below.

\[
Z_{in} = n\pi \left( \frac{\rho c}{S_p} \right) \left( \frac{1}{2Q_n} + j(\Omega_n - 1) \right) \tag{6.10}
\]

- \( S_p \) = pipe cross sectional area
- \( Q_n \) = Quality factor of the nth resonant mode
- \( \Omega_n = f/f_0 \); where \( f \) = pipe resonant frequency, \( n \) = modal number of \( f \)
- \( f_0 \) = calculated fundamental of pipe.

In both equations 6.9 and 6.10, \( Z_{in} \) has a reactive and a resistive term.

\( Z_{in} \) (of eqn. 6.9) = \( Z_{in} \) (of eqn 6.10) if;

\[
j\tan(K - jK') = n\left( \frac{1}{2Q_n} + j(\Omega_n - 1) \right) \tag{6.11}
\]

Morse\textsuperscript{63} gave the equation for the specific acoustic impedance at the driving end of an open pipe with an infinite flange, \( z_i \), (i.e. the input specific acoustic impedance) as:

\[
z_i = -j\rho c \left[ \frac{\tan\left(2\pi \frac{L_z}{\lambda}\right) + j2\pi^2 \left(\frac{a}{\lambda}\right)^2}{1 - j2\pi^2 \left(\frac{a}{\lambda}\right)^2 \tan\left(2\pi \frac{L_z}{\lambda}\right)} \right] \tag{6.12}
\]

\textit{for } \lambda > 8\pi a

and

\[
z_i = \left( \rho c - j\frac{\rho c^2}{\pi \omega a} e^{j4\pi \frac{L_z}{\lambda}} \right) \tag{6.13}
\]

\textit{for } \lambda < \pi a/3
where \( L_e = \) acoustic (effective) length of the pipe = \( L + 8a/3\pi \)

If the pipe flange is infinitesimally small, \( L_e \) becomes \( L + 0.6a \). The pipes under study were flangeless, assumed to have infinitesimally small flanges.

\( \lambda = \) the wavelength of the sound, \( a = \) pipe radius, \( c = \) speed of sound in air and \( \rho = \) the density of air.

The pipe under study met the requirements stipulated for equation 6.12 (i.e. \( \lambda > 8\pi a \)), hence that equation was used.

For a pipe cross sectional area of, \( S_p \), the analogous electrical input impedance, \( Z_{in} \), is given by the equation

\[
Z_{in} = \frac{Z_l}{S_p} = -j\frac{\rho c}{S_p} \frac{\tan \left( \frac{2\pi L_e}{\lambda} \right) + j2\pi^2 \left( \frac{a}{\lambda} \right)^2}{1 - j2\pi^2 \left( \frac{a}{\lambda} \right)^2 \tan \left( \frac{2\pi L_e}{\lambda} \right)} \tag{6.14}
\]

\( Z_{in} \) is made up of a real and an imaginary part, i.e. a resistance and a reactive component.

Fletcher's formula\(^{32}\) for \( Z_{in} \) has the loss parameter \( K' \) which is proportional to \( \omega^{0.5} \). The constant of proportionality has to be determined. Determining \( Z_{in} \) from Fletcher's formula is not straight forward.

Yoshikawa and Saneyoshi's\(^{98}\) formula require prior knowledge, or experimental measurements of acoustic data from the test rig that would in turn be used to determine the pipe resonance quality factor. The input impedance can be wholly resistive if \( \Omega_n = 0 \).
Morse's formula\textsuperscript{63} for $Z_{in}$ looks complicated but is easier to compute. It relies mainly on geometric measurements of the pipe for its parameters. The Morse formula (equation 6.14) was used to evaluate $Z_{in}$.

Fletcher's (equation 6.9)\textsuperscript{32}, Yoshikawa and Saneyoshi's(equation 6.10)\textsuperscript{98} and Morse's(equation 6.14)\textsuperscript{63} equation for $Z_{in}$ will yield the same result if

$$jn \tan (K-jk^1) = \pi n \left( \frac{1}{2Q_n} + j \left( \Omega_n - 1 \right) \right) = j \frac{\tan \left( \frac{2\pi L_e}{\lambda} \right) + j2\pi^2 \left( \frac{a}{\lambda} \right)^2}{1 - j2\pi^2 \left( \frac{a}{\lambda} \right)^2 \tan \left( \frac{2\pi L_e}{\lambda} \right)}$$

6.2.2 Pipe Mouth Impedance

In their investigation of the feedback excitation mechanism of organ pipe sound, Yoshikawa and Saneyoshi,\textsuperscript{98} developed an equation for the acoustic mouth impedance, $Z_m$ as in equation 6.15,

$$Z_m \approx j \left( \frac{\rho \omega_o}{S_{eff}} \right) (n\Omega_n) L_m \text{.............................................6.15}$$

where, $S_{eff}$ = effective cross sectional area of mouth ($S_{eff} = (S_m S_p)^{0.5}$)

$S_m$ = mouth area; $S_p$ = cross sectional area of the pipe

$L_m$ = length of pipe mouth; $\Omega_n = f/nf_o = \omega/n\omega_o$

$f_o$ = calculated fundamental frequency of the pipe; i.e. $f_o = c/2L_e$

$L_e$ = pipe acoustic length; $c$ = speed of sound
\[ L_m = \frac{3d}{1 + \frac{S_m}{S_p} + \left(\frac{S_m}{S_p}\right)^{0.5}} \] .......................... 6.16

and

\[ S_{\text{eff}} = (S_mS_p)^{0.5} \] .......................... 6.17

\( d = \text{distance between the lip (jet nozzle of pipe) and edge} \)

\( S_m = \text{mouth area} \)

\( S_p = \text{cross sectional area of the pipe} \)

\( \Rightarrow \text{if } S_p \gg S_m; L_m \approx 3d \)

\( \text{if } S_m \approx S_p; L_m \approx d \)

Yoshikawa and Saneyoshi's\textsuperscript{98} estimations of \( L_m \) and \( S_{\text{eff}} \) were based on the assumption that the pipe mouth was equivalent to the circular truncated cone of height \( L_m \), whose volume was equivalent to the mouth volume.

In their study of jet-resonator interaction in organ pipes, Fletcher and Rossing\textsuperscript{35} derived an expression for the mouth impedance for pipes with resonant frequencies that are "not too high", \( Z_m \), as

\[ Z_m = \frac{j\omega \Delta L}{S_p} \] .................................................. 6.18

where \( \Delta L = \text{end correction of the open mouth} \).
From his analysis of the pipe as an electrical circuit, Morse suggested that a hole in the wall of a cylindrical tube is analogous to a shunted resistance and inductance. Morse worked out the mouth inductance $L_m$ and resistance, $R_m$ as given below:

$$R_m = \frac{\rho \omega^2}{2 \pi c} = \frac{\rho \omega}{\lambda} \quad 6.19a$$

$$L_m = 0.5 \rho / a_m \quad 6.19b$$

where the mouth impedance $Z_m = R_m + j \omega L_m \quad 6.20$

where $a_m = \text{mouth radius}$

$\rho = \text{density of air}; \lambda = \text{wavelength}; c = \text{speed of sound}$.

The Fletcher & Rossing (equation 6.18) as well as the Yoshikawa and Saneyoshi (equation 6.16) formulas for the mouth impedance are purely reactive. They probably assumed, though did not state, that the resistive component of the mouth impedance was negligible.

If the value of the inductance was to be deduced from either Fletcher & Rossing's or Yoshikawa and Saneyoshi's formula, then $Z_m$ would be considered to be equivalent to the impedance, $Z_L$, of the inductor, $L$, where $Z_L = j \omega L$

such that, using Yoshikawa and Saneyoshi's formula (equation 6.15):

$$j \omega L = j \omega \rho (n \Omega) L_m (S_{\text{eff}})^{-1} \quad 6.21$$

$$L = \rho (n \Omega) L_m (S_{\text{eff}})^{-1} \quad 6.22$$

Using Fletcher & Rossing's formula (equation 6.18)
\[ j\omega L = j\omega \rho \Delta L (S_p)^{-1} \]  
\[ L = \rho \Delta L (S_p)^{-1} \]

If \( \omega n \Omega \approx 1; S_p \approx S_{\text{eff}} \) and the length of Yoshikawa and Saneyoshi's\(^{98}\) conceptual cone \( \approx \Delta L \); then the Yoshikawa and Saneyoshi, & Fletcher and Rossing\(^{35}\) formula would yield similar results for \( Z_m \).

\( \Delta L (S_p)^{-1} \) and \( L_m (S_{\text{eff}})^{-1} \) have the limiting value of \( 1/(2a_m) \).

and \( \omega (n \Omega) = 1 \), then all three formulas should yield similar values for (inductance) \( L_m \).

Morse's formula was used for consistency. The equation for the input impedance was based on the equation of the specific acoustic impedance of the pipe input as derived by Morse.

### 6.2.3 Pipe Resonator Impedance

The pipe resonant column can be considered to have a distributed inductance per unit length, \( L_p = \rho / S_p \) per unit length; and a distributed capacitance per unit length; \( C_p' \), given by

\[ C_p' = S_p (\rho c^2)^{-1} \]  
\[ 6.25 \]

The analogous capacitance and impedance of the resonance column becomes

\[ L_p = \rho L / S_p \]  
\[ 6.26 \]

and
C_p = V_p(\rho c^2)^{-1} \quad \text{6.27}

where \( V_p \) = pipe volume (= \( S_p L_p \)).

The impedance due to the inductance (\( Z_L \)) and capacitance (\( Z_C \)) are given by the equations:

\[
Z_L = j\omega L_p / S_p
\]

and

\[
Z_C = -j(\rho c^2)(\omega V_p)^{-1}
\]  \( \text{6.28} \)

Morse\(^63\) and Lighthill\(^50\) have showed that the pipe resonant frequency \( f_r \) is related to \( C_p \) and \( L_p \) by the equation:

\[
f_r = 1/2\pi(L_p C_p)^{0.5}
\]  \( \text{6.29} \)

### 6.2.4 Pipe Termination Impedance

Morse\(^63\) worked out the limiting values of the specific acoustic impedance at the open termination of an organ pipe with an infinite flange, \( z_o \), as:

\[
z_o = \frac{\rho \omega^2 a^2}{2c} - j\omega \left( \frac{8\rho a}{3\pi} \right) \quad \text{6.30a}
\]

for \( \lambda > 8\pi a \)

\[
z_o = \rho c - j2 \frac{\rho c^2}{\pi a \omega} \quad \text{6.30b}
\]

for \( \lambda < \pi a/3 \)

The imaginary term in equation 6.30a is equivalent to a mass air of value \( 8\rho a/3\pi \) \( \text{gcm}^{-2} \). For flangeless pipes, this term reduces to 0.6\( \rho a \). Recalling that the analogous electrical impedance is obtained by dividing the specific acoustic impedance by the cross sectional area of the pipe, \( S_p \), the equivalent electrical termination impedance, \( Z_T \), for flangeless
pipes becomes:

\[ Z_T = \frac{\rho \omega^2 a^2}{2cS_p} + \frac{0.6\omega a}{jS_p} \] \hspace{1cm} 6.31

The reactive component of \( Z_T \) is capacitance. The impedance, \( Z_T \), of a capacitance, \( C_T \), is given by the expression:

\[ Z_C = \frac{1}{j\omega C_T} \] \hspace{1cm} 6.32

If \( Z_c = \frac{0.6\omega a}{jS_p} \)

\[ \Rightarrow C_T = \frac{S_p}{0.6\omega a} \] \hspace{1cm} 6.33a

and

\[ R = \frac{\rho \omega^2 a^2}{2cS_p} \] \hspace{1cm} 6.33b

6.5 Rules of Arrangement of Circuit Components

It was shown earlier that the resonance column of the pipe is made up of a distributed capacitance and inductance. The position of these two components in the circuits is determined using guidelines outlined by Stephen and Bates. They give a set of guidelines for determining whether a specific circuit component should be placed in parallel or series relative to the rest of the circuit.

The rules they gave were:

(a) when a set of equivalent mechanical elements undergo the same displacement, they are to be connected in series,

(b) elements under the influence of the same force are to be connected in parallel,

(c) the stiffness between two consecutive elements in motion is equivalent to a shunt capacitance,
6.4 Arrangement of Circuit Components of Electrical Equivalent Circuit

Let the mouth, input, pipe inductance, pipe capacitance and termination impedances be represented respectively by $Z_m$, $Z_{in}$, $Z_{lp}$, $Z_{cp}$, and $Z_T$.

It has been shown that a hole on the side of a tube, which is what the pipe mouth is, is equivalent to an inductance and resistance shunted across at the appropriate point.\footnote{Coltman applied this concept in his electrical analogy of a flute. His impedance was purely reactive. A legitimate assumption if the hole is very narrow relative to the tube perimeter.}

Coltman\footnote{Following the arguments of Morse, the pipe equivalent circuit can be perceived to be equivalent to a circuit similar to figure 6.3.} applied this concept in his electrical analogy of a flute. His impedance was purely reactive. A legitimate assumption if the hole is very narrow relative to the tube perimeter.\footnote{Following the arguments of Morse, the pipe equivalent circuit can be perceived to be equivalent to a circuit similar to figure 6.3.}

The mouth impedance $Z_m$ in parallel with the equivalent impedance, $Z'_{eq}$, of the combination of the input, pipe and termination impedances ($Z_{in}$, $Z_{lp}$, $Z_{cp}$ and $Z_T$).
As the full circuit is developed in the ensuing stages outlined below, the manner in which $Z_{in}$ (input impedance) $Z_{lp}$ (reactance due to pipe inductance) $Z_{cp}$ (reactance due to pipe capacitance) and $Z_T$ (termination impedance) combine will be shown.

$Z'_{eq}$ is taken as being in parallel rather than in series following Fletcher and Rossing's electrical analogue of the regenerative excitation mechanism that describes jet excitation of organ pipe resonators. In it, they show the generator admittance, $Y_g$ linked to the overall pipe admittance in a parallel combination as per figure 6.4. This scheme was adopted from Yoshikawa and Saneyoshi's analysis - an analysis which produced fairly accurate results.

![Fig. 6.4 Pipe circuit model - development stage II]

$Y_p$ represents the input, pipe and termination impedances, assuming $Z'_{eq} = 1/Y_p$.

Logically, the current flow encounters the input impedances after the mouth. The input impedance had earlier been shown to be made up of a reactive and resistive term. Figure 6.3 can now be modified to include input impedance $Z_{in}$ as illustrated in figure 6.5 below.
Chapter 6: On an Electrical Analogous Circuit of the Organ Pipe for Turbulence Studies

Fig. 6.5 Pipe circuit model - development stage III

\[ Z_m = \text{mouth impedance and } Z_{\text{in}} = \text{input impedance} \]

\[ Z'_{\text{eq}} \text{ now comprises the pipe and termination impedances: } Z_{Lp}, \text{ (reactance due to pipe inductance) } Z_{cp}, \text{ (reactance due to pipe capacitance) and } Z_T, \text{ (termination impedance).} \]

The pipe distributed capacitance and inductance are subjected to the same pressure force and can therefore be connected in parallel following rule b (section 6.5). Expanding figure 6.5 to include the pipe capacitance and inductance; \( Z_{cp} \) and \( Z_{Lp} \) respectively, we have figure 6.6 below.

Fig. 6.6 Pipe circuit model - development stage IV

\[ Z_{Lp} = \text{reactance due to pipe inductance } Z_{cp} = \text{reactance due to pipe capacitance, } Z_m = \text{mouth impedance and } Z_{\text{in}} = \text{input impedance} \]

\[ Z'_{\text{eq}} = \text{equivalent circuit impedance of remaining components.} \]
This leaves just the positioning of the termination impedance $Z_T$.

The "buffer volume" of the surrounding atmosphere at the open end of the pipe can be constructed as a termination capacitance. The termination impedance at the outlet was shown to be made of a resistive and a reactive element. This "buffer volume" subjects the motion of the vibrating column that extends just beyond the open end to some frictional resistance. Stephen and Bates\textsuperscript{87} referred to this resistance as the "viscous resistance". The buffer volume in the vicinity of the pipe mouth is subjected to the displacement of the vibrating air column. Following the rules outlined by Stephen and Bates\textsuperscript{87} the elements that make up $Z_T (= R_T + 1/(j\omega C_T)$: termination resistance and capacitance respectively) can be connected in series and then introduced as a shunt impedance in place of $Z_{eq}'$ as depicted in Fig 6.7 below.

\begin{center}
\includegraphics[width=\textwidth]{pipe_circuit}
\end{center}

*Fig 6.7 Pipe circuit model - final stage*

$Z_{Lp}$ = reactance due to pipe inductance $Z_{cp}$ = reactance due to pipe capacitance, $Z_m$ = mouth impedance, $Z_{in}$ = input impedance, $Z_T$ = termination impedance and $Z_{in}$ = input impedance

### 6.5 Calculation of Circuit Impedances

The equations for the different circuit elements were used to evaluate the resistances, capacitances and inductances of the different circuit elements. Equation 6.14 was used in evaluating $Z_{in}$, $Z_m$ was determined using equation 6.20, $Z_{Lp}$ and $Z_{cp}$ were determined using
equations 6.26 and 6.27 respectively, while equation 6.33 was used to calculate $R_T$ and $C_T$. The component values were calculated using the mathematical package Maple\textsuperscript{TM} Version 2.100 (Maple is a software used to perform symbolic or numerical mathematical calculations). The program flow chart is given in appendix 10.

6.6 Computer Simulation of Pipe Analogous Circuits

The values of the circuit components were used to simulate the circuit using the circuit simulation package HSPICE\textsuperscript{47} The circuit was designed on the ECAD package Powerview\textsuperscript{1}, where from a wire listing of the circuit was automatically generated for HSPICE simulation.

6.6.1 Circuit Simulation Results

Using the parameter values computed the simulation yielded resonance frequencies with much lower resonant frequencies than the acoustic resonance frequencies as shown below in table 14

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Calculated $f_r$(Hz)</th>
<th>Acoustic $f_r$(Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>93.89</td>
<td>260.5</td>
</tr>
<tr>
<td>2</td>
<td>193.22</td>
<td>520.3</td>
</tr>
<tr>
<td>3</td>
<td>397.62</td>
<td>1078.8</td>
</tr>
<tr>
<td>4</td>
<td>784.28</td>
<td>2085.5</td>
</tr>
</tbody>
</table>

The results of the calculations yielded inaccurate frequencies, as such an ECAD simulations was not undertaken, for these set of component values.

---

1. Powerview is an electronic CAD package for designing circuits in preparation for HSPICE simulation.
In figure 6.7 (repeated below for clarity) it was indicated that the driving mechanism not only excites the resonance column of the pipe. There is coupling between the generator and the resonance column as well as feedback.

The mouth area and the pipe input both have inductance elements. If there is coupling between these two segments, it can be inferred that there will be some "coupling" between the passive elements. This would mean there is some coupling between the mouth and input inductance. The coupling gives rise to a mutual inductance, \( M_L \) which is proportional to the square root of the product of the input and mouth inductance; i.e.

\[
M_L \propto (L_{in}L_m)^{0.5}.
\]

\( L_{in} \) depends on the pipe length, from equation 6.17.

\( \Rightarrow \) \( L_m \) also depends on pipe length and of course, \( M_L \).

It can thus be argued that the whole pipe length does not fully participate in the resonance process. Resonance could only be taking place within a certain active length of the pipe, \( L_a \).

The sound generated propagates within the entire pipe, with the portion that constitutes the
active length, \( L_a \) serving as the radiation source. \( L_a \) would therefore be only a fraction of \( L_e \), the acoustic length of the pipe.

The pipe resonator capacitance and inductance values (equations 6.25 and 6.34) were recomputed substituting \( L_a \) in place of \( L_e \). The amount of coupling is not exactly known, hence \( L_a \) was determined by trial and error. A value of \( L_a = L_e/3 \) was found to yield a resonant frequency very close to the acoustic resonance frequency.

### 6.6.2. Circuit Simulation using the Pipe Active Length.

The component values were recomputed using \( L_a \). The new values of the circuit parameters are as in table 15 below.

<table>
<thead>
<tr>
<th>Component</th>
<th>Pipe 1</th>
<th>Pipe 2</th>
<th>Pipe 3</th>
<th>Pipe 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_m (\Omega) )</td>
<td>38.8</td>
<td>155.16</td>
<td>667.8</td>
<td>2493.3</td>
</tr>
<tr>
<td>( L_m (\text{mH}) )</td>
<td>0.729</td>
<td>1.24</td>
<td>1.97</td>
<td>3.13</td>
</tr>
<tr>
<td>( R_{in} (\Omega) )</td>
<td>0.3</td>
<td>0.618</td>
<td>0.732</td>
<td>0.958</td>
</tr>
<tr>
<td>( L_{in} (\text{mH}) )</td>
<td>99.6</td>
<td>7.59</td>
<td>0.36</td>
<td>2.1</td>
</tr>
<tr>
<td>( C_p (\mu\text{F}) )</td>
<td>246.9</td>
<td>53.6</td>
<td>8.11</td>
<td>1.21</td>
</tr>
<tr>
<td>( L_p (\text{mH}) )</td>
<td>1.421</td>
<td>1.6</td>
<td>2.54</td>
<td>4.42</td>
</tr>
<tr>
<td>( R_T (\Omega) )</td>
<td>0.015</td>
<td>0.06</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>( C_T (\mu\text{F}) )</td>
<td>2693.4</td>
<td>14.88</td>
<td>19.2</td>
<td>2.78</td>
</tr>
<tr>
<td>( f_r (\text{Hz}) )</td>
<td>268.7</td>
<td>543.8</td>
<td>1109.2</td>
<td>2177.7</td>
</tr>
</tbody>
</table>

The circuit simulation produced the resonance curves given in figures 6.16 - 6.19. The resonant frequencies are very similar to theoretically calculated values as well as those obtained from acoustic experiments as shown in table 16 below.
### Table 16: Calculated Simulated and Acoustic Resonant Frequencies of Pipe

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Calculated $f_r$ (Hz)</th>
<th>Simulated $f_r$ (Hz)</th>
<th>Acoustic $f_r$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>268.7</td>
<td>269.153</td>
<td>260.5</td>
</tr>
<tr>
<td>2</td>
<td>543.8</td>
<td>529.645</td>
<td>520.312</td>
</tr>
<tr>
<td>3</td>
<td>1109.2</td>
<td>1064.14</td>
<td>1078.812</td>
</tr>
<tr>
<td>4</td>
<td>2177.7</td>
<td>2114.26</td>
<td>2084.5</td>
</tr>
</tbody>
</table>

**Note:** For figures 6.8 - 6.11, the horizontal axis is on a log scale.

![Graph](image.png)

\[ f_r = 269.2 \]

**Fig 6.8 Response of HSPICE simulation of the equivalent circuit of pipe 1**
Chapter 6: On an Electrical Analogous Circuit of the Organ Pipe for Turbulence Studies

Fig 6.9 Response of HSPICE simulation of the equivalent circuit of pipe 2

Fig 6.10 Response of HSPICE simulation of the equivalent circuit of pipe 3
6.6.3 The Study of Turbulence Effects by Electrical Circuit Simulation.

After establishing that the appropriately adjusted circuit operates at the approximate resonant frequency, simulation experiments were conducted to evaluate the effects of turbulence on its performance.

The electronic CAD package, Powerview has standard input signals that can be used as input into a circuit for simulation. The signals are sinusoidal, digital and exponential functions. None was random or white noise.

In chapter 3, it was shown that grids of the turbulence spectrum has a Gaussian distribution. Since noise has a similar distribution, it implies that turbulence could be simulated as broadband noise.

A noise generator circuit, as per figure 6.12 was designed, built on a vero board and
The noise generator circuit of figure 6.12 produces noise thanks to the break down noise generated by the diode, DD, which is in turn amplified by the transistor amplifier, T. While break down materializes physically, the simulation package could not deliver this effect, hence the there was no noise output. It turns out that HSPICE can only produce output to a circuit if the circuit is excited by a specific input. The noise generator has no input. As stated before, it relies on the break down noise of the diode DD.

The noise generator circuit was connected through a unity gain summing circuit that had two inputs into the pipe equivalent circuits. The other input to the summing circuit was an a.c. signal that swept through a range of frequencies. It is capable of sweeping through frequencies ranging from 1Hz to several mega Hertz. The a.c. sweep was programmed to sweep from a range of 1Hz to 10KHz as the frequency response is not expected to provide any additional information beyond 10KHz.
Figure 6.13 gives a block diagram of the circuit arrangement.

When it was realised that the noise generator could not deliver noise during the ECAD simulation, Gaussian noise was numerically simulated and inserted as a signal input into the programme routine of the wire listing automatically generated by Powerview for HSPICE simulation. The set of random numbers that simulated the Gaussian distribution (noise) were generated using MINTAB™. Even then, HSPICE could not handle the computation and the excercise was discontinued. An example of a modified program listing as described above is in appendix 12).

As the noise circuit was not producing the expected result, it was left out of the simulation and the system as per the block diagram of figure 6.14 was used.
The simulation experiments produced the frequency responses given earlier in figures 6.8 - 6.11.

As the noise generator could not be relied on to provide a computer simulation of turbulence, it was necessary to carry out a hardware implementation of the system.

6.6.4. Evaluating Pipe Analogous Circuits by Experiment.

Each of the pipe circuits was constructed. A noise generator and function generator supplied a signal, into the circuits via a unity gain summing amplifier.

The function generator used was a FG600 Function Generator by Feedback. An HP HO1-3722A Noise Generator by Hewlett Packard was used to provide the noise. The noise generator has a maximum output amplitude of 3.16 V rms. The control panel was tuned to deliver broadband white noise. The sequence length of the shift registers in the noise generator was set to infinite. The clock period was set to 50KHz. The Hewlett Packard noise generator provides analogue and digital noise outputs. The analogue output is obtained by converting the pseudo random digital noise output. Horowitz and Hill\textsuperscript{45} have shown that if the sequence length of a pseudo random bit sequence is infinite, the digital noise will require an infinitely large amount of time to repeat itself. The repeat time being...
the \((\text{sequence length})/\text{(clock frequency)}\). The numerator is infinite; dividing the numerator by a small finite denominator yields an infinite result, i.e. an infinite repeat time of the sequence.

The summing circuit was built around a 741 operational amplifier. The amplifier was powered with a Farnell Standard Power Supply, delivering \(\pm30\text{V}\) maximum.

On the acoustic test rig, the flow into the wind chest was arranged such that different proportions of filtered (laminar) wind and turbulent wind flowed downstream into the wind chest. Valves were used to deliver wind in the proportions as per table 5 (chapter 5) repeated below in table 17 for clarity.

<table>
<thead>
<tr>
<th>Percentage turbulent flow</th>
<th>Percentage laminar flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>

The flow combinations of the above table had to be mimicked electrically. The volumetric flow current, \(Q\), is analogous to the electrical current.

\[ Q = US_d \]

6.34

Where \(S_d\) = duct cross sectional area. \(U\) implicitly will be directly proportional to the analogous electric current.

Hinze\(^{41}\) showed that the instantaneous velocity of flow;
\[ U = U + u \]  \hspace{1cm} \text{(6.35)}

where \( U \) is the mean flow velocity and \( u \) the fluctuation about the mean. Hinze further defines the turbulence intensity as:

\[ u'/U, \]  \hspace{1cm} \text{(6.36)}

where \( u' \) is the root mean square value of \( u \).

\( U \) can be taken to represent the sinusoidal electrical current emanating from the function generator and the current from the noise generator to represent the turbulent fluctuations about the mean flow, \( u' \). Then

\[ u'/U \times 100\% \]  \hspace{1cm} \text{(6.37)}

would be a percentage of turbulence flowing into the system.

A Blackstar 3210 true rms multimeter was used to measure the output currents of the noise and signal generators.

The current output for the different control knob position of both the signal and noise generators are as in table 18 below.
Table 18: Current Output of Signal and Noise Generators

<table>
<thead>
<tr>
<th>Control Knob Position</th>
<th>Signal Generator Output current (mA rms)</th>
<th>Noise Generator Control Knob Position</th>
<th>Noise Generator Output current (mA rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>0.428</td>
<td>0.1</td>
<td>0.32</td>
</tr>
<tr>
<td>2</td>
<td>0.947</td>
<td>0.2</td>
<td>0.91</td>
</tr>
<tr>
<td>3</td>
<td>1.46</td>
<td>0.3</td>
<td>1.29</td>
</tr>
<tr>
<td>4</td>
<td>2.27</td>
<td>0.4</td>
<td>1.81</td>
</tr>
<tr>
<td>5</td>
<td>2.86</td>
<td>0.5</td>
<td>2.17</td>
</tr>
<tr>
<td>6</td>
<td>3.42</td>
<td>0.6</td>
<td>2.65</td>
</tr>
<tr>
<td>7</td>
<td>3.95</td>
<td>0.7</td>
<td>3.12</td>
</tr>
<tr>
<td>8</td>
<td>4.6</td>
<td>0.8</td>
<td>3.51</td>
</tr>
<tr>
<td>9</td>
<td>5.18</td>
<td>0.9</td>
<td>3.96</td>
</tr>
<tr>
<td>10</td>
<td>5.81</td>
<td>1</td>
<td>4.42</td>
</tr>
</tbody>
</table>

From the above table, the turbulence/laminar conditions are worked out using equation 6.37 and are given in table 19.

Table 19: Electrical Equivalence of Flow Conditions

<table>
<thead>
<tr>
<th>Turbulence Flow %</th>
<th>Laminar flow %</th>
<th>Signal Current (mA)</th>
<th>Noise Current (mA)</th>
<th>Noise/Signal %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
<td>3.95</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>75</td>
<td>5.18</td>
<td>1.29</td>
<td>24.9</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>4.6</td>
<td>2.17</td>
<td>47.17</td>
</tr>
<tr>
<td>75</td>
<td>25</td>
<td>5.81</td>
<td>3.51</td>
<td>76.1</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>0.16</td>
<td>4.42</td>
<td>100</td>
</tr>
</tbody>
</table>
These settings were used to simulate the appropriate turbulence/laminar flow conditions into the circuit.

The function generator, unlike that used for the computer simulation, does not automatically sweep through a range of frequencies, it could only be set to one frequency at a time.

While the noise generator was switched off, the function generator was panned till the resonant frequency of the circuit was reached - as observed on an oscilloscope. The noise generator output was then set accordingly and then switched on. The output was spectrally analyzed on the B & K spectrum analyser and the spectrum printed on an HP plotter. The circuit outputs for the different combinations of noise and sinusoidal inputs (representing the different combinations of turbulent and laminar flow) are given in figures 6.15 - 6.34
Chapter 6: On an Electrical Analogous Circuit of the Organ Pipe for Turbulence Studies

Fig 6.16 Response of hardware equivalent circuit of pipe 1 (25% Turbulence)

Fig 6.17 Response of hardware equivalent circuit of pipe 1 (50% Turbulence)

Fig 6.18 Response of hardware equivalent circuit of pipe 1 (75% Turbulence)

..118..
Chapter 6: On an Electrical Analogous Circuit of the Organ Pipe for Turbulence Studies

Fig 6.19 Response of hardware equivalent circuit of pipe 1 (100% Turbulence)

Fig 6.20 Response of hardware equivalent circuit of pipe 2 (0% Turbulence)

Fig 6.21 Response of hardware equivalent circuit of pipe 2 (25% Turbulence)
Chapter 6: On an Electrical Analogous Circuit of the Organ Pipe for Turbulence Studies

Fig 6.22 Response of hardware equivalent circuit of pipe 2 (50% Turbulence)

Fig 6.23 Response of hardware equivalent circuit of pipe 2 (75% Turbulence)

Fig 6.24 Response of hardware equivalent circuit of pipe 2 (100% Turbulence)
Chapter 6: On an Electrical Analogous Circuit of the Organ Pipe for Turbulence Studies

Fig 6.25 Response of hardware equivalent circuit of pipe 3 (0% Turbulence)

Fig 6.26 Response of hardware equivalent circuit of pipe 3 (25% Turbulence)

Fig 6.27 Response of hardware equivalent circuit of pipe 3 (50% Turbulence)
Fig 6.28 Response of hardware equivalent circuit of pipe 3 (75% Turbulence)

Fig 6.29 Response of hardware equivalent circuit of pipe 3 (100% Turbulence)

Fig 6.30 Response of hardware equivalent circuit of pipe 4 (0% Turbulence)
Chapter 6: On an Electrical Analogous Circuit of the Organ Pipe for Turbulence Studies

Fig 6.31 Response of hardware equivalent circuit of pipe 4 (25% Turbulence)

Fig 6.32 Response of hardware equivalent circuit of pipe 4 (50% Turbulence)

Fig 6.33 Response of hardware equivalent circuit of pipe 4 (75% Turbulence)
Chapter 6: On an Electrical Analogous Circuit of the Organ Pipe for Turbulence Studies

It is observed that the output curve does not change significantly for the different input combinations. A closer examination of the pipe analogous circuits indicates that they are principally passive resonant circuits. At resonance, such circuits behave like narrow band pass filters, neglecting all input except those with frequencies at or very near the resonance point. The pipe circuits exhibited the characteristic behaviour expected of resonant circuits.

Another approach is therefore required to conduct this study. In studying the transient sounds produced by organ pipe action, Caddy and Pollard\(^9\) developed electrical equivalent circuits. They intimated that the parameters of the pallet control action electrical circuit analogue were non-linear. It is possible that the equivalent circuit parameters of the circuit analogue of the pipe also exhibit non-linear characteristics.

**Table 20: Calculated, Simulated, Acoustic and Hardware \(f_r\) of Pipe Circuits**

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Calculated (f_r) (Hz)</th>
<th>Simulated (f_r) (Hz)</th>
<th>Acoustic (f_r) (Hz)</th>
<th>Hardware (f_r) (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>268.7</td>
<td>269.153</td>
<td>260.5</td>
<td>270.625</td>
</tr>
<tr>
<td>2</td>
<td>543.8</td>
<td>529.645</td>
<td>520.312</td>
<td>518.250</td>
</tr>
<tr>
<td>3</td>
<td>1109.2</td>
<td>1064.14</td>
<td>1078.812</td>
<td>990.875</td>
</tr>
<tr>
<td>4</td>
<td>2177.7</td>
<td>2114.26</td>
<td>2084.5</td>
<td>2044.625</td>
</tr>
</tbody>
</table>

Fig 6.34 Response of hardware equivalent circuit of pipe 4 (100% Turbulence)
6.6.5 Non-linearity of Circuit Components of Organ Pipe Analogous Circuits.

It is well known that the pitch of the organ pipe changes with blowing pressure and flow speed.\(^{12,32,39,40}\) Recalling that the pressure is analogous to voltage potential and volume flow current (and hence flow speed) analogous to current, it can be argued that the resonance frequency of the pipe analogous circuit should be dependent on the current flowing through the circuit components (or the voltage drop across each component). The circuit parameters should be capable of delivering a higher or lower resonant frequency with changing current. This suggests that the circuit parameters should be a function of the current flowing into the circuit. It could be either the function of current or voltages since one is dependent on the other.

Let's re-examine the equivalent pipe circuit developed earlier and illustrated below in figure 6.35.

![Electrical Equivalent Circuit of Organ Flue Pipe](image)

**Fig 6.35: Electrical Equivalent Circuit of Organ Flue Pipe**

- \(R_m\) Mouth resistance;
- \(C_m\) Mouth capacitance;
- \(R_{in}\) Input resistance;
- \(L_{in}\) Input inductance;
- \(C_p\) Pipe capacitance;
- \(L_p\) Pipe inductance;
- \(R_T\) Termination resistance; and
- \(C_T\) Termination capacitance - \(E(s)\) is the driving potential.

The components can be reduced into impedance blocks such that figure 6.35 can be
redrawn in the manner depicted in figure 6.36.

Fig 6.36: Electrical Equivalent Circuit of Organ Pipe in Impedance Blocks

\[ Z_p = \text{reactance due to pipe inductance & capacitance}, \quad Z_m = \text{mouth impedance}, \quad Z_T = \text{termination impedance} \quad \text{and} \quad Z_{in} = \text{input impedance} - I_s \text{ source current, } I_{in} \text{ pipe input current, } I_m \text{ mouth current} \]

The exact non-linear behaviour of the different components is not known. The thrust of this research is not aimed at determining the expression that defines the non-linear conduct of the analogous circuit components. However, it is within the remit of this work to suggest a method of analysis that could be used to study the effects of turbulence on the pipe sound quality, using the analogous electrical circuit. In the ensuing theoretical analysis, a proposal is given as to how turbulence studies can be carried out once the non-linear character of the circuit parameters can be physically defined.

If the assumption that the circuit parameters are functions of voltage or current is correct, then the impedances can be expressed as follows:

\[ Z_{in} = Z_{in}(I_{in}) \]
\[ Z_m = Z_m(I_m) \]
\[ Z_p = Z_p(I_p) \]
\[ Z_t = Z_t(I_t) \]  

where \( Z_p = \frac{Z_{cp}}{Z_{Lp}} \)

Since the current in the circuit will be time dependent, it implies the impedances will also be time dependent. At a particular time, \( t \), say, there will be a specific value of \( E(s) \) and \( I(s) \) flowing into the circuit and hence instantaneous values of \( I_m, I_{in}, I_p \) and \( I_t \) giving an instantaneous value of the impedance elements: \( Z_m, Z_{in}, Z_p \) and \( Z_T \). At this instant, the overall equivalent impedance, \( Z_{eq}(t) \) of the circuit can be computed using the expression:

\[ Z_{eq} = \frac{(Z_p/Z_t + Z_i)\overline{Z_m}}{Z_m} \]

For any two dummy variables, \( A \& B \) expressed in the form \( A/B \), it implies:

\[ A/B = (1/A + 1/B)^{-1} \]

From the current divider rule:

\[ I_{in} = I_sZ_m/(Z_i + Z_m) \]

\[ I_t = I_iZ_p/(Z_p + Z_T) \]

\[ I_t = \left\{ \frac{Z_p/(Z_p + Z_T)}{(Z_m/(Z_m + Z_i))} \right\} I_s \]

\[ E(s) = I_m/Z_m \]

Using equations 6.51-6.54, an expression for the system function can be worked out. The system function at a particular instant, \( t \), following Papoulis\textsuperscript{71} is given by the expression:
\[ \frac{I_f}{E(s)} = \frac{I_f}{I_m} \left\{ \frac{Z_p}{(Z_p + Z_T)} \right\} \left\{ \frac{1}{(Z_m + Z_i)} \right\} = h(t) \] 6.45

The magnitude of \( h(t) \) can then be plotted against time, to give the time domain response. The frequency domain response (spectral characteristic) of the equivalent circuit(s) can be determined by taking the Fourier transform of the time domain response.

If the current into the circuit is a combination of the noise and sinusoidal currents, then the spectral response mentioned above would be the frequency response of the pipe equivalent circuit. By combining different ratios of noise and signal, different flow conditions can be simulated and different frequency response curves obtained that would provide some information on the effects of turbulence on the pipe sound quality.
CHAPTER 7

OTHER APPLICATIONS AND PROPOSALS FOR FURTHER RESEARCH

Some of the developments from this research could be applied in other areas of aeroacoustics. Further developments can be added to what has been achieved. The ensuing discussion advances suggestions as to how the foregoing can be attained.

7.1 Other Applications of this Research

The findings of this research are likely to find applications beyond the realms of musical organs.

Research carried out in USA, France, Holland, Germany, Hungary UK and Australia in the different domains of aero-acoustics have borrowed from the hypothesis advanced from investigations into the flow acoustic interaction in organ pipes.

7.1.1 Resonance Effects in Moving Vehicles

In USA Elder has applied some of the theories developed from the studies of the jet drive mechanism of organ pipes to the understanding of cavity resonance generated by jets in moving vessels in research conducted for the US Navy. Some of his findings involved modelling the jet drive mechanism as an electrical analogous circuits. Perhaps some of the developments in chapter 6, dealing with the electrical analogue of an organ pipe could find application in the research they are conducting.
7.1.2 Studying Pulsations in Gas Plants

Research conducted in Holland has made use of the aero-acoustics mechanism in organ pipes to understand pulsations at T-junctions, closed side branches, stilling chambers and compressor stations at the gas plants of Nederlandse Gasunie (NG). Peters\textsuperscript{72,73} also conducted experiments to evaluate flow induced pulsations at safety relief valves which can cause fracture. The research for NG were conducted for flow that had low Mach numbers with high Reynolds numbers. The research was geared mainly to eliminate the resonance, unlike in the organ pipe situation where it is desirable.

As customers to the gas plant switch on and off their gas appliances, the volumetric flow rate of gas through the pipelines will change, changing the Reynolds number of the flow and hence turbulence flow condition. How would these variations affect the pulsations at the compression stations, stilling chambers, valves and junctions? The analysis of the effects of changing levels of turbulence on pipe sound could be adapted for such a study.

Some investigations were carried out to understand the effects of changing flow speeds on the pressure fluctuations. Braggeman,\textsuperscript{8} showed there was a shift in pulsation frequency with changing speed. In organ pipes increasing the flow rate of wind into the pipes produces sound of higher pitch. Braggeman's work may need to be extended to take into consideration the effects of various levels of turbulence, at constant flow speeds on these pulsations as well the nature of the deleterious effects they cause.

If gas pipe lines are modeled as electrical circuits (perhaps using transmission line theory) and subsequently analysed, more light could be shed on the nature of the pulsations. The electrical analysis could also provide an alternative method for analysing the problem, theoretically and by simulation.
7.1.3 Other Applications in Organs

In some organs bass pipes are stood off the sound board and wind supply is tubed to them via a small flexible hose, usually less than 3 cm in diameter. In chapter 4, it was shown that one of the methods for suppressing turbulence was by using a helically coiled wind trunk. If the turbulence of the wind into the sound board was attenuated, then channelling wind via a helically wound hose into the organ pipe foothole will suppress any further generation of turbulence in the transit of the air to the pipe.

7.2 Proposals for Further Research

In the development of electrical analogous circuits of the organ pipe, this study did not look into the feedback mechanism around the mouth of the pipe. The analogue of coupling between the mouth and input as well as the pipe outlet and surrounding atmosphere were not incorporated within the circuit. The initial objective was to get an approximate linear model. On achieving this it was realised that a more accurate model of the circuit would require non-linear electrical components. More work will have to be done to develop a non-linear analogue circuit of the pipe. When this has been achieved, introducing the phenomenon of feedback and coupling encountered in acoustic systems will shed even more light on the behaviour of the organ pipe.

It is possible that organ wind trunks, sound boards and the key chamber can be modelled as electrical circuits, it may not be long before an electrical model of the entire system is developed.

Such techniques could be adapted to model gas pipelines, stilling chambers and compressor stations. In chapter 6, a suggestion is given as to how a non-linear electrical equivalent circuit of the organ pipe, when worked out, could be analysed. It maybe less time consuming, and perhaps even cheaper, to simulate the performance of a pipe via its electrical analogue than by aero-acoustic experiments or Finite Element Analysis.
CHAPTER 8

CONCLUSIONS

This research began by surveying the development of organ blowing mechanisms from human operated blowers through to centrifugal blowers, giving their advantages and disadvantages. Several trips were undertaken to over a dozen different sites to look at the blowing mechanisms used to supply wind to the organs and also observe the sound quality produced.

In order to understand the effects of turbulence on organ sound, the nature of turbulence itself had to be understood. Investigations showed that turbulence had similar statistical characteristics to broad band noise.

Investigating the effects of turbulence on pipe sound quality required the turbulence levels to be varied to see how varying it affects pipe sound. Different techniques for suppressing and or attenuating turbulence were examined. Amongst those considered were: channel enlargement, spanwise axis rotation of the flow channel, helically coiled pipes as well as flow stratification. Of all these techniques only that of flow stratification could attenuate turbulence in flows with Reynolds numbers (Re) exceeding 20000. In organ blowing situations, Reynolds numbers greater than 50000 are usually encountered.

A turbulence attenuator designed for St. Paul's Hall, University of Huddersfield was built and tested and found to have a cut off frequency of 3.8 KHz. The organ pipe sound with and without the turbulence filter installed was evaluated aurally, qualitatively and quantitatively.
Turbulence effects can be represented qualitatively using spectrographs

It was noted there was a shift in resonance frequencies. Ripples in the leading and trailing edges of the spectrum of the different fundamentals were much reduced after turbulence attenuation. Two resonant peaks observed in the F#₄₃ 8 ft Gedackt resolves to one after the pipe was supplied with turbulence attenuated wind.

Turbulence effects are significant and perceivable

An aural evaluation of the turbulence attenuator (St. Paul's) also indicates there were significant improvements in the tonal quality of the pipes. Some registers lost their acidity, others had a better blend, while others had a more penetrating tone. Additional experiments on a laboratory test rig corroborated the aural perceptions observed in St. Paul's. It has been established that changing the levels of turbulence of wind flowing into organ pipes, perceivably influences the pipe sound quality. This inference was drawn from an aural evaluation of the sound from pipes on the laboratory test rig blown with wind with a variety of turbulence levels, by a number of music students. With less turbulence the pipes on the test rig were found to produce "more pure ... and clearer sound" which had more "bite". In addition, the notes were considered more stable and smoother. Most of these improvements where thought to be experienced largely with the lower registers.

Turbulence effects can be quantified using the concept of moments

A mathematical technique was developed to quantify the changes in pipe sound with changing effects of turbulence. The concept of statistical moments was used to achieve this. The spectrum of the fundamentals of the different pipes on the test rig were normalized and the third and fourth moments about the fundamental evaluated.

It was found that the spectrum of the pipe fundamentals all have a negative symmetry (i.e. were skewed to the left). The skewness was accentuated with increasing laminar flow. The fourth moment, which measured the "peakedness" of the pipe fundamental, was found to
increase with increasing laminar flow of wind into the organ.

☐ Turbulence causes frequency shifts in the pitch
It was further observed that decreasing turbulence intensity produces a frequency shifted to the right (got sharper) or to the left (got flatter) depending on whether the pipes were nicked or not, respectively. Frequency shifts of about 0.3% were observed. These shifts are perceivable. This behaviour maybe explained only after a detailed analysis of the effects of fluid flow and pressure have on the acoustic propagation of the the whole system.

☐ Organ pipes can be modelled as electrical circuits for turbulence studies
Several other researchers have conducted their studies into the sound generation mechanism of organ pipes by using electrical analogous circuits. They used circuit analogues for studying the effects of pressure fluctuations within the key chamber, feedback mechanism at the pipe mouth, the jet drive mechanism of the pipe resonator and initial transients that occur when the pipe foot hole is first opened. A technique for modeling the pipe circuit as an electrical circuit for turbulence studies was also undertaken.

A circuit model of the flue organ pipe similar to those used on the experimental test rig was developed. The components of the electrical equivalent circuit were calculated from appropriate equations. These equations contain physical properties of air. They are also dependent on the geometric dimensions of the pipe. An electrical simulation of the circuit on HSPICE gave resonant frequencies well below expected/measured values.

The aero-acoustics of organ pipes involves coupling between the pipe mouth and pipe inlet as well as the outlet and atmosphere. The coupling, it was argued, gives rise to a mutual inductance between the pipe mouth and pipe resonant column. The mutual inductance is also dependent on the pipe length. It is inferred that the whole pipe length may not fully be participating in the resonant process. Resonance is most likely taking place within a certain active length, $L_a$, which is less than the geometric of the pipe, $L_g$. The sound generated
propagates within the entire geometric length of the pipe, however, only the active length is the radiation source. Through trial and error, an \( L_a = \frac{L_e}{3} \) was found to give circuit component values that yielded resonant frequencies closer to the experimental values.

Electronic CAD (ECAD) simulation studies on the pipe circuits for turbulence were successfully carried out to evaluate the resonance frequencies of the circuits. However this technique could not be fully realised because the CAD package, HSPICE, available could not simulate a noise circuit to represent turbulence. Modifications to the wirelisting program generated by the drawing package, POWERVIEW for HSPICE simulation, to include numerical values of noise (turbulence) could not be compiled because the package could not handle tasks of such complexity.

Hardwired circuits of the pipes were built and tested. Various magnitudes of noise signal simulating turbulence and a sinusoid signal voltages tuned to the pipe resonant frequency, were applied to the circuit. The circuits are found to exhibit resonance effects at frequencies similar to those obtained by computer simulation and experimental test rig. However no major changes in spectral characteristics were observed with changing levels of turbulence (noise). The analogous electrical circuits of the different pipes are principally passive resonance circuits. At resonance, such circuits usually behave like narrow band pass filters, transmitting only frequencies at or very near the vicinity of the resonant point. The pipe circuits are most likely to have been exhibiting a similar behaviour. It is likely that a non-linear circuit model of the pipe may exhibit a behaviour similar to the behaviour of the observed organ pipe.

The detailed analysis of a circuit with non-linear components is beyond the scope of this work, however, it appears that such a study may be useful for simulating the effects of turbulence in a general case, including the organ pipe and wind delivery system.
APPENDICES

APPENDIX 1

Some notes on the St Paul’s organ

The stop list, details of wind pressures plus some information on the console as well as pipe scaling are outlined below.

Stop List

The stops on the 3 manuals and pedal are as outlined in table 1 below.

Table 21: Pipe stops for St Paul’s

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tremulant</td>
<td>Tremulant</td>
<td>Tremulant</td>
<td>Tremulant</td>
</tr>
<tr>
<td>Cromhorne (8)</td>
<td>Trompete (8)</td>
<td>Trompete (8)</td>
<td>Schalmei (4)</td>
</tr>
<tr>
<td>Cymbel III (1/2)</td>
<td>Trompete (16)</td>
<td>Basson (16)</td>
<td>Trompete (8)</td>
</tr>
<tr>
<td>Sesquialtera II (2 2/3)</td>
<td>Scharf IV (1)</td>
<td>Scharf IV (1)</td>
<td>Posaune (16)</td>
</tr>
<tr>
<td>Octave (1)</td>
<td>Mixture IV-VI</td>
<td>Tierce (1 2/3)</td>
<td>Mixture VI (2 2/3)</td>
</tr>
<tr>
<td>Quinte (1 1/2)</td>
<td>Gemshorn (2)</td>
<td>Waldflute (2)</td>
<td>Nachthorn (2)</td>
</tr>
<tr>
<td>Principal (2)</td>
<td>Spitzflute (4)</td>
<td>Nazard (2 2/3)</td>
<td>Octave (4)</td>
</tr>
<tr>
<td>Rohrflute (4)</td>
<td>Octave (4)</td>
<td>Koppelflute (4)</td>
<td>Rohr Gedackt (8)</td>
</tr>
<tr>
<td>Praestant (4)</td>
<td>Rohrflute (8)</td>
<td>Principal (4)</td>
<td>Octave (8)</td>
</tr>
<tr>
<td>Gedackt (8)</td>
<td>Principal (8)</td>
<td>Holz Gedackt (8)</td>
<td>Subbass (16)</td>
</tr>
<tr>
<td>III - I a</td>
<td>Gedacktpommer (16)</td>
<td>Spitzgamba (8)</td>
<td>Principal (16)</td>
</tr>
<tr>
<td>III - II a</td>
<td></td>
<td>Celeste tc (8)</td>
<td>III - Pedal c</td>
</tr>
<tr>
<td>Cymbelstern b</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I - II a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II &amp; Pedal Combs. d</td>
<td></td>
<td></td>
<td>II - Pedal c</td>
</tr>
<tr>
<td>III on Pedal pistons d</td>
<td></td>
<td></td>
<td>I - Pedal c</td>
</tr>
<tr>
<td>I on Pedal pistons d</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a. III-I: III-II: I-II are manual couplers (i.e. when down, manual III plays on manual 1 etc.)
b. A series of small bells hit by hammer
c. III-P: II-P: I-P are manual to pedal couplers (i.e. when drawn, the bottom 32 notes of manual III are coupled to the pedals etc. 1

d. These stops offer methods of controlling the computer based registration system fitted to the organ
Wind Pressure

The design pressure for the manuals and pedals are as follows:
Manual I, 53 mmH₂O; Manual II, 60 mmH₂O; Manual III, 63 mmH₂O and Pedal, 70 mmH₂O

Pipe Scales

The pipe diameter (in mm) for the stops used in the experiment are as given in Table 2 below:

Table 22: Some Pipe Scales for St Paul’s

<table>
<thead>
<tr>
<th>Stop</th>
<th>Pitch (ft)</th>
<th>C₁</th>
<th>C₁₃</th>
<th>C₂₅</th>
<th>C₃₇</th>
<th>C₄₉</th>
<th>C₆₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gedackt</td>
<td>8</td>
<td>102</td>
<td>65</td>
<td>42</td>
<td>27</td>
<td>17</td>
<td>G₉₅⁷ gemshorn⁺</td>
</tr>
<tr>
<td>Rohrflute</td>
<td>4</td>
<td>70</td>
<td>44</td>
<td>27</td>
<td>16</td>
<td>G₉₄₅⁷ gemshorn⁻</td>
<td></td>
</tr>
<tr>
<td>Principal</td>
<td>2</td>
<td>44</td>
<td>25</td>
<td>15</td>
<td>9</td>
<td>5.6</td>
<td>4</td>
</tr>
</tbody>
</table>

⁺ Stopped pipes can not be made above G₅₆ at 8 ft pitch, the corresponding pipe at 4 ft pitch, G₉₅⁷ gemshorn is used. A similar rule applies for the C₄₉, Rohrflute.

The author was informed by the organ builders that the pipes were scaled using the Rensch System. The a₂₂ (4 ft Principal) was set to 440 Hz. This setting is usually determined by the organ builder on the basis of the specification supplied by the person/organisation commissioning the organ.

The organ builders also indicated that the diameter of the flue pipes, except flutes, were halved not on every octave but on the 17th note. The flutes were halved on the 16th note.

Details of the scales of the other pipes are available in: The Concert Organ of St Pauls, Nov 1977; published by the University of Huddersfield

The Organ Console

The organ console is made up of 3 manuals (equivalent to the Keyboard - played by hand), the pedals (equivalent to a keyboard operated with feet) and the stops. Each manual has 61 notes. The notes are the same for each manual. The three manuals are: manual I (choir organ); manual II (great organ) and manual III (swell). The method of indicating notes is as follows:

Manuals:- Compass, C₁ C₂ D₃ D₄ E₅ F₆ F₇ G₈ G₉ A₁₀ A¹₁ B₁₂ C₁₃..C₂₅..C₃₇..C₄₉..C₆₁
C₁ is bottom C (bass), C₂₅ (middle C) and C₆₁ top C (treble)

Pedals:- Compass, C₁ C₂ D₃ D₄ E₅ F₆ F₇ G₈ G₉ A₁₀ A¹₁ B₁₂ C₁₃..C₂₅..G₃₂
C₁ is bottom C₁₃ (bass) and G₃₂ top G (treble)
Pitches are indicated by stop and note e.g. 4 ft Principal A₂₂ is tuned to 440 Hz
A - G are sliders.  
Each slider is marked with a letter appropriate to its position on scale.  
When the a stop is pulled it pulls a slider(s). Each slider has holes in it which when the slider is pulled, is aligned with the toe hole of the pipe and allows wind into the pipe foot.  

(More details on the soundboard can be found in *The Organ*, by J. Perrot, Oxford University Press, 1971, ch12)
APPENDIX 3

A3 A Theoretical Overview of Turbulence

A3.1 Turbulence: Some Definitions

Imagine some fluid, say, air or water, flowing in a channel with rigid walls. The flowing fluid molecules encounter frictional forces at the walls as it flows, giving rise to "spinning" of the fluid at the wall boundary. This "spinning" is similar to the spinning of a moving ball when it hits a rigid wall. The "spinning" gives rise to eddies and vortices that introduce fluctuations within the mean flow of the fluid. These fluctuations can either be velocity or pressure fluctuations or both. These fluctuations in motion are referred to as turbulence.

If appropriate sensing devices are used to monitor the turbulence, it should exhibit a random amplitude and spread across a broad frequency band.

Bradshaw has a more complex definition of turbulence. He defines it as: A three dimensional time-dependent motion in which vortex stretching causes velocity fluctuations to spread to all wavelengths between a minimum determined by viscous forces and a maximum determined by the boundary conditions of the flow. [This is the] state of flow in all fluid motion except those with low Reynolds numbers."

Defining turbulence in terms of "wavelengths" or wavenumber is a misnomer as this implies that turbulence has a velocity of propagation and can accommodate the sort of analysis that would be used in electromagnetic waves, acoustic waves etc. It is more sensible to consider turbulence fluctuations to be spread across different frequencies within the spectral band of turbulence under study.
Appendices

Hinze argues that the fundamental characteristics of turbulence in fluids is "irregular motion". These irregular motions are random in space and time, i.e. for a given point in the flow, the instantaneous values of the turbulence motions are not predictable, rendering it difficult to define the function of turbulence motion. Accepting Hinze's arguments to be valid, these fluctuations, could be better understood by using some principles of probability and statistics.

A3.2 The Statistical Nature of Turbulence

The statistical analysis of turbulence, borrows from amongst several, the works of Hinze, Bradshaw, Bendat and Piersol and the Russian Physicists Smol' yakov and Tkachenko. Correlation techniques shall be used in the spectral analysis of the turbulence. The turbulence signal emanating from a turbulence sensor, shall be analysed using spectral techniques.

Measurements on the turbulent nature of the airflow were taken using a hot wire anemometer and spectrum analyser.

A3.2.1 Assumptions made on the statistical nature of turbulence

The measurements taken were analysed exploiting some assumptions based on concepts in Statistics and Probability, namely:

1. That the turbulence signal from the transducer, is a continuous random variable. That is; in the observation of the turbulence signal in the time domain, over a definite or indefinite interval (impractical), the signal continuously has an unpredictable (or indeterminate) value.

2. In the experiments conducted for this work, turbulence measurements were made on the assumption that the flow was homogenous. Smol' yakov and Tkachenko
argue that flow is homogenous along streamlines parallel to the duct wall if the duct has a constant cross-section and is "long enough". The long rectangular ducts used in our experiments ensured these conditions were met. As far as practicable, flow measurements were taken at distances of 20 times the hydraulic (equivalent) diameter, $D_e$, of the duct down stream.

Where $D_e$ is given by the equation:\(^{21}\)

$$D_e = \frac{4 \times \text{Area}}{\text{Perimeter}} \tag{3.1}$$

It is further assumed that the turbulence fluctuations are statistically stationary (see illustration of figures a1 & a2). This assumption is only valid if the one dimensional probability density function of the turbulence signal is time independent.

---

1. A note on homogenous fluid flow:

If a plane perpendicular to the duct wall and the flow of a fluid in a duct is taken, and turbulence monitored at different points within the plane, and it is observed that the turbulence situation is different at each point, then the flow exhibits spatial inhomogeneity. In other flow situations, the turbulence at the same point in the plane may vary with time: this variation yields a time inhomogenous situation.
The moment, $\mu_n$, of a continuous signal $[x(t)]$ is prescribed by the equation:

$$142.$$
such that for $m = 1$, $\mu_1$ = the mean of the value of the flow characteristic under consideration.

So if $p(x)$ was describing the probability density of the velocity fluctuations, $\mu_1$ would yield the mean flow velocity. If the probability density function, $p(x)$, is not constant, the moment of the signal will not be constant.

4 If in addition to the homogenous and the statistically stationary property, the time and ensemble average of the turbulence fluctuations are assumed to be identical, then the turbulence signal can be described as ergodic.

This is a very useful assumption as measurements and subsequently spectral analysis of the turbulence signal, involves the averaging of this signal in individual realisations over a time period rather than an ensemble of realisations.

A3.3 Spectral Analysis of Turbulence

It can be assumed that the velocities of the fluid in the different turbulent motions have their corresponding frequency band. Because of the random nature of these motions, an average amount of their Kinetic Energy would be expected to be devoted to some very small but finite individual frequency band over a range of frequencies.\textsuperscript{41}

It would be unrealistic to say that this energy is concentrated on discrete frequencies because this would imply that turbulence exhibits wave characteristics; a phenomenon earlier discounted.

The spreading or distribution of this average energies over the different frequencies yields
the Energy Spectral Density (also called, the Power Spectral Density or Energy Spectrum or Spectral Density)

The purpose of studying the spectrum of turbulence of the air supplied to organs, is to elucidate the acoustic effects of turbulence rather than its fluid dynamic character.

The spectrum of the turbulence signal was obtained using the B&K dual channel spectrum analyser (model 2340).

A3.3.1 Principles of Correlation Techniques in the Spectral Analysis of Turbulence

The superposition of the vortices and various eddies within the flowing fluid generally induce (turbulence) random motions about the mean flow velocity such that the instantaneous value of the velocity could be written as:

\[ U = \bar{U} + u \]

where; \( \bar{U} \) = average velocity and \( u \) velocity of random fluctuation, with the time average of random fluctuations, \( \bar{u} = 0 \) and the average of the absolute value of the turbulence fluctuations, \( |\bar{u}| \) = measure of the aggression of the fluctuation\(^{41} \) (these should not be confused with \( u' (= \sqrt{\bar{u}^2}) \), the intensity of turbulence).

If two temporal history records of the turbulence signal are taken from two sensors \( S_x \) and \( S_y \) providing signals \( X(t) \) and \( Y(t) \) say, then the procedure for determining the dependence of \( Y(t) \) on \( X(t) \) or vice versa, for continuous ergodic data, following Bendat and Piersol\(^6 \) is via the cross covariance function, \( C_{yx} \), between the signals of \( S_x \) and \( S_y \) as given in equation 3.4 below.
\[ C_{yx}(\tau) = E \{ Y(t) - \mu_y \} \{ X(t+\tau) - \mu_x \} \] ...........................................3.4

\[ E[] = \text{Expectation of []}; \mu_x \text{ and } \mu_y = \text{mean values of } X(t) \text{ and } Y(t) \text{ respectively} \]
\[ \tau = \text{spatial distance in the time domain between sensors.} \]

Following appendix 3B:

\[ C_{yx}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_0^T \{ Y(t) - \mu_y \} \{ X(t+\tau) - \mu_x \} \, dt \] ...........................................3.5

\[ .......... = R_{yx}(\tau) + \mu_y \mu_x ......................................................3.6 \]

where;

\[ R_{yx} = \lim_{T \to \infty} \frac{1}{T} \int_0^T (Y(t)X(t+\tau)) \, d\tau \] ...........................................3.7

\[ R_{yx}(\tau) = \text{crosscorrelation between } Y(t) \text{ and } X(t) \]

Using Fourier transform techniques, the cross power spectral density of the continuous and ergodic time history records of the signals \( Y(t) \) and \( X(t) \) can be determined. This is realised by taking the Fourier Transform of the cross correlation function of these records in the manner prescribed by equation 3.8 below,

\[ S_{yx}(\omega) = \int_{-\infty}^{\infty} R_{yx}(\tau) e^{-j2\pi\omega\tau} \, d\tau \] ...........................................3.8
$S_{yx}(f) =$ Cross power spectral density function.

If $Y(t) = X(t)$ i.e. the signals are from the same source then equation 3.8 transforms into:

$$S_{yy}(f) = \int_{-\infty}^{\infty} R_{yy}(\tau) e^{-j2\pi ft} d\tau .................................................. 3.9$$

Since $R_{yy}(\tau)$ is an even function;
i.e. $R_{yy}(-\tau) = R_{yy}(\tau) \Rightarrow S_{yy}(f)$ is also an even function.

In this situation, $S_{yy}(f) =$ Auto power spectral density function or Autospectrum.

In practice, signal analysis is mainly concerned with the positive frequencies, hence if this practical understanding were applied to the equation 3.9; only evaluations from zero to $\infty$ would be considered which after a few arithmetic manipulations would yield the one-sided auto power spectral density function, $G_{yy}(f)$, where;

$$G_{yy}(f) = 2S_{yy}(f) = 2 \int_{-\infty}^{\infty} R_{yy}(\tau) e^{-j2\pi ft} d\tau .......... \forall (f \geq 0) .......... 3.10$$

$$= 0 \hspace{1cm} \forall (f < 0)$$

i.e.

$$G_{yy}(f) = 2S_{yy}(f) = 2 \int_{-\infty}^{\infty} R_{yy}(\tau) \{ \cos (2\pi ft) + j \sin (2\pi ft) \} d\tau .......... 3.11$$

$$\forall f \geq 0$$

$$= 0 \hspace{1cm} \forall f < 0$$

Knowing that $R_{yy}(\tau) = R_{yy}(-\tau)$ it implies that the one-sided autospectrum can be extracted from the real part of the Fourier transform in equation 3.11, such that:

$$G_{yy}(f) = 4 \int_{0}^{\infty} R_{yy}(\tau) \cos (2\pi ft) d\tau .......... .................................................. 3.12$$

that is: the one-sided power spectral density function (or one-sided autospectrum, when $S_y$
of the turbulence signal emanating from the turbulence sensor can be obtained by taking the real component of the positive frequencies of the Fourier transform of the cross correlation (or autocorrelation) of the signal.

Given the random nature of the turbulence fluctuations, its time domain signal is expected to be similar to broadband noise. The autospectrum should reveal the frequency span of the turbulence signal.

The size of the eddies inducing the turbulence depends on the duct size and the character of the vortices; the latter resulting in a decrease in the size of the eddies with increase in wind speed. These in turn are expected to influence the frequency span of the turbulence signal.
APPENDIX 3B

A-3.4 Derivation of the Covariance for two Random Continuous Data

Given a random variable, \( Y(t) \), with \( \mu_y \) and \( \sigma_y^2 \) as its mean and variance respectively and with a probability density \( p(y) \): if (like a turbulence signal) the random variable, \( Y \), is a Continuous function \( f(Y) \) \( \forall \) real \( Y \), then the mathematical expectation of \( f(Y) \) is given by the equation:

\[
E[f(Y)] = \int_{-\infty}^{\infty} f(Y) p(y) \, dy \tag{a1}
\]

Let \( f(Y) = Y^m \) \( \forall m \in \{1^+ > 0\} \); equation \( a1 \) will become

\[
E[(Y^m)] = \mu_{y,m} = \int_{-\infty}^{\infty} Y^m p(y) \, dy \tag{a2}
\]

\( E(Y^m) \) is known as the \( m^{th} \) moment of \( f(Y) \)

when \( m = 0 \); (i.e. 0 th moment) \( \mu_{y,0} = 1 \)
when \( m = 1 \); (i.e. 1st moment) \( \mu_{y,1} = \mu_y \)
when \( m = 2 \); (i.e. 2nd moment) \( \mu_{y,2} = \Psi^2 \) (the mean sq. value of \( y(t) \))

If \( f(Y) \) is substituted by \( (Y- \mu_y)^n \) instead, then;

\[
E[(Y- \mu_y)^n] = \int_{-\infty}^{\infty} (Y- \mu_y)^n p(y) \, dy \tag{a3}
\]

\( E[(Y - \mu_y)^n] \) is known as the \( n^{th} \) central moment of \( f(Y) \)

[Note: when \( n=2 \); eqn. \( a3 \) yields, \( \sigma \), the variance i.e. the 2nd central moment]

If \( f(Y) \) is continuous and ergodic data in the time domain, and captured over a time frame, \( T \),
then the 2nd central moment from equation a3 can be re-written as:

$$E \left[ (y(t) - \mu_y)^2 \right] = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} (y(t) - \mu_y)^2 dt$$ ...........................................a4

Consider two ergodic and continuous data $y(t)$ and $x(t)$ with a time delay of, $\tau$, between them. If in addition we wish to determine the linear relationship between them, this can be obtained by evaluating the cross covariance, $C_{yx}(\tau)$, of these datum via equation a5 below:

$$C_{yx}(\tau) = E[(y(t) - \mu_y)\{x(t + \tau) - \mu_x\}]$$ ...............................................................a5

substituting eqn. a5 into eqn. a4, yields eqn. a6, below

$$C_{yx}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} \{y(t) - \mu_y\} \{x(t + \tau) - \mu_x\} dt$$ ...............a6

$$= \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} y(t)x(t + \tau) dt - \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} \mu_y y(t) dt - \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} \mu_x x(t + \tau) dt + \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} \mu_y \mu_x dt$$

I II III IV...a7

Expression:  I = $R_{yx}(\tau)$

II = III = 0: $y(t)$ & $x(t+\tau)$ are Continuous random variables, while $\mu$ is constant; the time average of such variables always yield zero. 6

IV = $$\lim_{T \to \infty} \frac{1}{T} \left[ \mu_y \mu_x \right]^{T}_{0} = \mu_y \mu_x$$

$$\Rightarrow C_{yx} = R_{yx} + \mu_y \mu_x$$
APPENDIX 4

A-4 Calculations for the Turbulence Suppressor Built for St. Paul’s

Given that honeycomb dimensions of suppressor are: (ID) 2.4 mm x 3.5 mm and an OD of 2.8 mm x 3.7 mm, the blockage ratio of the honeycomb, $\beta$, = $(3.5 \times 2.4) / (3.7 \times 2.8) = 0.8108$.

![Effective area of each passage](image)

*Fig. a 4; Dissection of Suppressor Passage.*

**Determination of $R_e$ before honeycomb passage:**

Given duct dimensions (of St. Paul’s) of 419 mm by 146 mm;
and maximum flow rate, Q, of centrifugal blower of 1200 cubic ft./min. (i.e. = 0.5663 m$^3$/s)
⇒ Mean flow velocity, U, of $Q/A$ (= 9.258 m/s) and a Hydraulic Diameter;

\[ D_e = 4A/P = 0.2165; \] where $P =$ perimeter of duct and $A =$ Area of duct.

Assuming viscosity, $\mu$, and density of air, $\rho$, to be $1.8 \times 10^{-5}$ Ns/m$^2$ and 1.2 Kg/m$^3$ respectively, $R_e =$ \((UD_e\rho)/\mu\) evaluates to 133723 (>> 2300, the laminar to turbulent transition $R_e$)
Determination of $R_{e,p}$ within honeycomb passage

Dimensions of honeycomb = 100 mm x 419 mm x 292 mm.

Effective area of honeycomb, $A_e = \beta (419 \times 292) \, \text{mm}^2 = 0.0992 \, \text{m}^2$.

Mean velocity through passage $U_p = Q/A_e = 5.7087 \, \text{m/s}$

Passage hydraulic diameter, $d_e = 4A_e/P_p = 2.85 \, \text{mm}$;

where $P_p = \text{Perimeter of each passage of the honeycomb}$.

These parameters yield an $R_{e,p} = (\rho U_p d_e)/\mu = 1085$

Now, the pressure drop across the passage, $\Delta p$, is given by:

$$\Delta p = (4\rho f L_w U_p)/2d_e; \text{ where, the friction factor, } f = 16/R_{e,p},$$

The foregoing parameters yield a $\Delta p$ of $40.62 \, \text{N/m}^2$
APPENDIX 5

A-5 Procedure for Checking the Frequency Response of the Constant Temperature Anemometer (CTA)

The frequency response of the HWA is determined using the experimental set up of figure a-2. A 1 KHz square wave from a signal generator is fed into the bridge input. The output of the CTA is displayed on an oscilloscope. The output should be similar to the simulated trace of figure a-3.

If the Pulse has a width, $\tau$, (for hot films), then the frequency response, $f = \tau^{-1}$.
APPENDIX 6

A-6 Questionaire on Research on the Effects of Turbulence on Organ Pipe Sound.

Year ...........................................................................................................................................

Instrument(s) Studied (i)...............................................................................................................

GROUP:..........................................................

FOUR pipes will be played under FOUR different conditions. On a Scale of 1 to 5 (1 = Horrible,
2 = Poor, 3 = Okay, 4 = Good, 5 = Brilliant) describe your appreciation of each note in the
second row of the table below. In the space provided in row three- use words from the list of
adjectives given in table two to further qualify your appreciation.

Note: There is a separate table for each pipe.

Pipe 1

Table 23: Musical Appreciation of Turbulence Effects

<table>
<thead>
<tr>
<th>Flow Conditions</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Describe Quality of Sound (Using 1-5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Using Adjectives in Table 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 24: List of Adjectives

| Smoother Pitch (SP) | Harsh (H) |
| Clearer Sound (CS) | Coarse (C) |
| Brighter (B) | Wobbles (W) |
| Purer (P) | Aggressive (A) |
| Steady (St) | Shrill (Sh) |
APPENDIX 7

A7.2 On (statistical) moments

A measure of the spread about the mean can be calculated in terms of the 2nd, 3rd and 4th moments. The 2nd moment is the variance of the data. The 3rd moment provides information on the degree of asymmetry relative to the mean. The 4th moment is a measure of the amount of peakedness or physical sharpness of the distribution relative to the mean.

A7.2.1 On the fourth moment

Figure a7.1 is an illustration of curve shapes that describe the variation in the 4th moments. A very flat distribution is platykurtic, a rounded peak is described as mesokurtic, while a sharp peak, leptokurtic

![Figure a7.1 Curve shapes for different types of 4th moments.](image)

A7.2.2 On the third moment
When the distribution is not skewed, the 3rd moment is zero.

A distribution can be skewed to the right or left. Skewness to the right (or positive skewness) implies the distribution tails more to the right than left and vice versa for skewness to the left (or negative skewness).

![Fig. a7.2 Distributions illustrating types of 3rd moments](image)

When moments relative to the mean are evaluated they are generally referred to as central moments.

The frequency of the note falls at the origin of the distribution of the curve of the fundamental. It is the changes in the distribution about the origin (rather than the mean) that is of interest. To quantify these changes, it would be reasonable for the moments to be taken about the magnitude of the origin, i.e. about the magnitude of the origin or centre frequency.

**A7.3 Numerical analysis of pipe fundamentals.**

If a variable, $X$, has $N$ different values; such that $X = X_n$, $\forall \ n = 1, 2, 3 \ldots N$, the $K^{th}$ moment of the variable, $X$, is given by equation a7.1 below:
$\bar{X}^k = \frac{\left( \sum_{n=1}^{N} (X_n^k) \right)}{N}$ ........................................... a7.1

i.e. $X^k = K^{th}$ moment of $X$

For $K = 1$;

$\bar{X}^1 = $ Arithmetic mean of $X$ ........................................... a7.2

The $K^{th}$ moment about the mean, $^1M_k$, is defined as the $K^{th}$ central moment, and is prescribed by the equation:

$^1M_k = \frac{\sum_{n=1}^{N} (X_n - \bar{X})^k}{N}$ ........................................... a7.3

When $K = 2$, $^1M_2 = $ second central moment or variance about the mean.

$K = 3$, $^1M_3 = $ 3rd central moment or degree of asymmetry relative to the mean.

$K = 4$, $^1M_4 = $ 4th central moment or degree of peakedness relative to the mean.

If the moments are computed about the magnitude of the origin, $\psi$ say, such that

$M_k = \frac{\sum_{n=1}^{N} (X_n - \psi)^k}{N}$ ........................................... a7.4
If $X_n$ and $\psi$ are not dimensionless, the dimensionless form of $M_3$ and $M_4$ would have to be determined in a manner given in equations a7.5 and a7.6, to yield, the moment coefficient of skewness, $M_{cs}$, and the moment coefficient of kurtosis, $M_{ck}$, respectively; where:

$$M_{cs} = \frac{M_3}{M_2^{1.5}} \quad \text{.......................... a7.5}$$

$$M_{ck} = \frac{M_4}{M_2^2} \quad \text{.......................... a7.6}$$

If the shape(distribution) of the fundamental changes about the centre frequency is to be studied, then, it would be proper to take moments about the centre frequency - in other words, compute $M_k$ (equation a7.4).

**A7.4 Application of principles of moments to evaluation of experimental data**

Notes that were to be analysed were played back into the spectrum analyser, and their power spectral density taken. The fundamental was zoomed into at $\pm 50$Hz about the central frequency. The cursor of the spectrum analyser was used to sample the readings of the magnitude of the curve at frequencies $\pm 10$Hz about the fundamental.

The change in the data within $\pm 1$Hz of the centre frequency was more drastic, hence samples within this range were taken in steps of $0.125$Hz or $0.0625$Hz; then $0.25$Hz, $0.5$Hz, later progressing to steps of $1$Hz on either side of the centre frequency. An example
of the sampled data, with the precise points of measurement for the different notes analysed is presented in appendix 8.

The peak magnitude of the fundamental varied from note to note. This varied for the same note under different blowing conditions. Though the microphone was held in the same position under laboratory conditions, all the measurements were not conducted on the same day.

In circumstances where the recordings where taken inside the organ of St. Paul's, it was difficult to maintain the position of the microphone as recordings where done on different days - in addition, the microphone position had to be adjusted frequently to obtain a high recording level on the DAT recorder.

In order to ascertan some level of uniformity in the data before analysis, the sampled spectrum was normalised. The illustration below describes the approach used.

Assume a note had a central (fundamental) frequency, \( f_c \) Hz, say, and the shape given in the example of figure a7.3 below.

![Fig a7.3 Sampling of frequency data for analysis](image)
The cursor was moved say to \( f_c - x \) Hz and its amplitude, \( A_x \) was read, through to \( f_c - 10 \) Hz. Similarly the amplitude of \( f_c \) Hz, \( A_{\max} \); \( f_c + y \) Hz, \( A_y \); etc. were taken till the frequency range, \( f_c \pm 10 \) Hz was covered.

\( A_{\max} \) varied for different notes. To get the same frame of reference for comparison, the data was normalised; such that \( A_{\max} = 1 \) and \( A_{\min} = 0 \) for all the data evaluated.

To transform a data point \( A_p \), to its normalised value \( A_{np} \), the following expression was used.

\[
A_{np} = \frac{A_p - A_{\min}}{A_{\max} - A_{\min}}
\]

Examples

\[
A_{nx} = \frac{A_x - A_{\min}}{A_{\max} - A_{\min}}
\]

\[
A_{n\max} = \frac{A_{\max} - A_{\min}}{A_{\max} - A_{\min}} = 1
\]

\[
A_{n\min} = \frac{A_{\min} - A_{\min}}{A_{\max} - A_{\min}} = 0
\]

\( \Rightarrow \ A_{nj} \ \forall \ j \) are now dimensionless entities.
It was earlier discussed that the moments are to be taken about the centre frequency, $f_c$. Since the magnitude of $f_c$ for the normalised curve is one for all notes, it implies the $k^{th}$ moment about the magnitude of $f_c$ would be equivalent to the $k^{th}$ moment about unity; from equation a7.5. This transforms equation a7.4 to equation a7.11 below

$$M_k = \frac{\left( \sum_{n=1}^{N} (X_n - 1)^k \right)}{N}$$ .................................a7.11

As such, when $k = 4$, it can be reasonably assumed that we have a measure of the physical sharpness of the fundamental. For $k = 3$, equation a7.11 computes the skewness of the data.

A comparative examination of $M_4$ and $M_3$ about the fundamental frequency under different turbulence conditions would therefore provide some information on how turbulence affects the shape of the notes and therefore tonal quality.
APPENDIX 8a

A-8a Flow chart of MINITAB programme used to calculate moments

START

ENTER EQUATIONS OF MOMENTS

READ PIPE DATA FROM PRE-PREPARED TABLE

CALCULATE MOMENTS

OUTPUT RESULTS OF CALCULATIONS

EXIT PIPE DATA TABLE

END
Appendices

APPENDIX 8b

A-8b Sampled Data from St Paul’s (an example)

Generally:  

\[ \text{[ ]B4} = \text{Data sample of note [ ] before turbulence attenuation.} \]

\[ \text{NB4} = \text{Normalised data before turbulence attenuation} \]

\[ \text{NAFT} = \text{Normalised data after turbulence attenuation} \]

\[ \text{FREQ[\text{note}]} = \text{Frequency at which samples of note were taken} \]

<table>
<thead>
<tr>
<th>FREQC61</th>
<th>GEDC61B4</th>
<th>GEDC61AF</th>
<th>NB4</th>
<th>NAFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>-89.9</td>
<td>-96.6</td>
<td>0.092402</td>
<td>0</td>
</tr>
<tr>
<td>-9</td>
<td>-89.6</td>
<td>-94.2</td>
<td>0.098563</td>
<td>0.050209</td>
</tr>
<tr>
<td>-8</td>
<td>-86.4</td>
<td>-90.9</td>
<td>0.164271</td>
<td>0.119247</td>
</tr>
<tr>
<td>-7</td>
<td>-87.7</td>
<td>-90.3</td>
<td>0.137577</td>
<td>0.131799</td>
</tr>
<tr>
<td>-6.5</td>
<td>-83.8</td>
<td>-88.2</td>
<td>0.217659</td>
<td>0.175732</td>
</tr>
<tr>
<td>-6</td>
<td>-82.7</td>
<td>-88.9</td>
<td>0.240246</td>
<td>0.161088</td>
</tr>
<tr>
<td>-5.5</td>
<td>-81.8</td>
<td>-86.4</td>
<td>0.258727</td>
<td>0.213389</td>
</tr>
<tr>
<td>-5</td>
<td>-79.8</td>
<td>-84.6</td>
<td>0.299795</td>
<td>0.251046</td>
</tr>
<tr>
<td>-4.5</td>
<td>-81.2</td>
<td>-88.2</td>
<td>0.271047</td>
<td>0.175732</td>
</tr>
<tr>
<td>-4</td>
<td>-78.0</td>
<td>-84.8</td>
<td>0.336756</td>
<td>0.246862</td>
</tr>
<tr>
<td>-3.5</td>
<td>-78.4</td>
<td>-85.4</td>
<td>0.328542</td>
<td>0.23431</td>
</tr>
<tr>
<td>-3</td>
<td>-77.3</td>
<td>-82.5</td>
<td>0.351129</td>
<td>0.294979</td>
</tr>
<tr>
<td>-2.5</td>
<td>-75.7</td>
<td>-79.1</td>
<td>0.383984</td>
<td>0.366109</td>
</tr>
<tr>
<td>-2.25</td>
<td>-74.2</td>
<td>-76.1</td>
<td>0.414784</td>
<td>0.42887</td>
</tr>
<tr>
<td>-2</td>
<td>-72.6</td>
<td>-75.8</td>
<td>0.447639</td>
<td>0.435146</td>
</tr>
<tr>
<td>-1.875</td>
<td>-70.9</td>
<td>-76.6</td>
<td>0.482546</td>
<td>0.41841</td>
</tr>
<tr>
<td>-1.75</td>
<td>-69.5</td>
<td>-73.5</td>
<td>0.511294</td>
<td>0.483264</td>
</tr>
<tr>
<td>-1.5</td>
<td>-70.6</td>
<td>-73.3</td>
<td>0.488706</td>
<td>0.487448</td>
</tr>
</tbody>
</table>

Table 25: Gedackt C61

..162..
<table>
<thead>
<tr>
<th>FREQC61</th>
<th>GEDC61B4</th>
<th>GEDC61AF</th>
<th>NB4</th>
<th>NAFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.375</td>
<td>-69.1</td>
<td>-72.3</td>
<td>0.519507</td>
<td>0.508368</td>
</tr>
<tr>
<td>-1.25</td>
<td>-67.7</td>
<td>-70.2</td>
<td>0.548255</td>
<td>0.552301</td>
</tr>
<tr>
<td>-1.125</td>
<td>-67.5</td>
<td>-70.7</td>
<td>0.552361</td>
<td>0.541841</td>
</tr>
<tr>
<td>-1</td>
<td>-64.8</td>
<td>-69.9</td>
<td>0.607803</td>
<td>0.558577</td>
</tr>
<tr>
<td>-0.875</td>
<td>-64.2</td>
<td>-69.2</td>
<td>0.620123</td>
<td>0.573222</td>
</tr>
<tr>
<td>-0.75</td>
<td>-63.1</td>
<td>-67.3</td>
<td>0.642711</td>
<td>0.612971</td>
</tr>
<tr>
<td>-0.625</td>
<td>-59.3</td>
<td>-64.3</td>
<td>0.720739</td>
<td>0.675732</td>
</tr>
<tr>
<td>-0.5</td>
<td>-58.3</td>
<td>-62</td>
<td>0.741273</td>
<td>0.723849</td>
</tr>
<tr>
<td>-0.375</td>
<td>-55.1</td>
<td>-60.3</td>
<td>0.806982</td>
<td>0.759414</td>
</tr>
<tr>
<td>-0.25</td>
<td>-50</td>
<td>-55.4</td>
<td>0.911704</td>
<td>0.861925</td>
</tr>
<tr>
<td>-0.125</td>
<td>-46.7</td>
<td>-50</td>
<td>0.979466</td>
<td>0.974895</td>
</tr>
<tr>
<td>0</td>
<td>-45.7</td>
<td>-48.8</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0.125</td>
<td>-45.9</td>
<td>-51.1</td>
<td>0.995893</td>
<td>0.951883</td>
</tr>
<tr>
<td>0.25</td>
<td>-48.3</td>
<td>-56.5</td>
<td>0.946612</td>
<td>0.838912</td>
</tr>
<tr>
<td>0.375</td>
<td>-54.9</td>
<td>-61.1</td>
<td>0.811088</td>
<td>0.742678</td>
</tr>
<tr>
<td>0.5</td>
<td>-58.1</td>
<td>-62.4</td>
<td>0.74538</td>
<td>0.715481</td>
</tr>
<tr>
<td>0.625</td>
<td>-58.2</td>
<td>-65.9</td>
<td>0.743326</td>
<td>0.642259</td>
</tr>
<tr>
<td>0.75</td>
<td>-61.5</td>
<td>-68.2</td>
<td>0.675565</td>
<td>0.594142</td>
</tr>
<tr>
<td>0.875</td>
<td>-64.3</td>
<td>-69.6</td>
<td>0.61807</td>
<td>0.564854</td>
</tr>
<tr>
<td>1</td>
<td>-66.5</td>
<td>-71.2</td>
<td>0.572895</td>
<td>0.531381</td>
</tr>
<tr>
<td>1.125</td>
<td>-67.3</td>
<td>-72</td>
<td>0.556468</td>
<td>0.514644</td>
</tr>
<tr>
<td>1.25</td>
<td>-68.1</td>
<td>-73.8</td>
<td>0.540041</td>
<td>0.476987</td>
</tr>
<tr>
<td>1.375</td>
<td>-69.6</td>
<td>-73.4</td>
<td>0.50924</td>
<td>0.485356</td>
</tr>
<tr>
<td>1.5</td>
<td>-71.2</td>
<td>-74.3</td>
<td>0.476386</td>
<td>0.466527</td>
</tr>
<tr>
<td>1.75</td>
<td>-74.3</td>
<td>-75.7</td>
<td>0.412731</td>
<td>0.437239</td>
</tr>
<tr>
<td>1.875</td>
<td>-75.5</td>
<td>-76.1</td>
<td>0.38809</td>
<td>0.42887</td>
</tr>
<tr>
<td>2</td>
<td>-74.6</td>
<td>-75.3</td>
<td>0.406571</td>
<td>0.445607</td>
</tr>
<tr>
<td>2.25</td>
<td>-75.4</td>
<td>-78.3</td>
<td>0.390144</td>
<td>0.382845</td>
</tr>
</tbody>
</table>
### Table 25: Gedackt C61

<table>
<thead>
<tr>
<th>FREQC61</th>
<th>GEDC61B4</th>
<th>GEDC61AF</th>
<th>NB4</th>
<th>NAFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>-77.7</td>
<td>-79.6</td>
<td>0.342916</td>
<td>0.355649</td>
</tr>
<tr>
<td>3</td>
<td>-77.7</td>
<td>-83.7</td>
<td>0.342916</td>
<td>0.269875</td>
</tr>
<tr>
<td>3.5</td>
<td>-80.8</td>
<td>-84.3</td>
<td>0.279261</td>
<td>0.257322</td>
</tr>
<tr>
<td>4</td>
<td>-82.2</td>
<td>-83.8</td>
<td>0.250513</td>
<td>0.267782</td>
</tr>
<tr>
<td>4.5</td>
<td>-83.9</td>
<td>-87</td>
<td>0.215606</td>
<td>0.200837</td>
</tr>
<tr>
<td>5</td>
<td>-85.6</td>
<td>-85.9</td>
<td>0.180698</td>
<td>0.223849</td>
</tr>
<tr>
<td>5.5</td>
<td>-86.2</td>
<td>-87.4</td>
<td>0.168378</td>
<td>0.192469</td>
</tr>
<tr>
<td>6</td>
<td>-87</td>
<td>-88.6</td>
<td>0.151951</td>
<td>0.167364</td>
</tr>
<tr>
<td>6.5</td>
<td>-88.9</td>
<td>-89.5</td>
<td>0.112936</td>
<td>0.148536</td>
</tr>
<tr>
<td>7</td>
<td>-89.3</td>
<td>-88.5</td>
<td>0.104723</td>
<td>0.169456</td>
</tr>
<tr>
<td>8</td>
<td>-91.1</td>
<td>-91.2</td>
<td>0.067762</td>
<td>0.112971</td>
</tr>
<tr>
<td>9</td>
<td>-93.4</td>
<td>-90.9</td>
<td>0.020534</td>
<td>0.119247</td>
</tr>
<tr>
<td>10</td>
<td>-94.4</td>
<td>-92.4</td>
<td>0</td>
<td>0.087866</td>
</tr>
</tbody>
</table>
APPENDIX 9

A-9 Example of Test Rig Sampled Data

Table 26: Pipe 1 Data

<table>
<thead>
<tr>
<th>FREQ</th>
<th>LOT1</th>
<th>L2T7</th>
<th>L5T5</th>
<th>L7T2</th>
<th>L1T0</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>-53.4</td>
<td>-54.1</td>
<td>-53.6</td>
<td>-54.7</td>
<td>-54.3</td>
</tr>
<tr>
<td>-9</td>
<td>-52.7</td>
<td>-54.1</td>
<td>-53</td>
<td>-54</td>
<td>-54.3</td>
</tr>
<tr>
<td>-8</td>
<td>-53.6</td>
<td>-56.7</td>
<td>-53.1</td>
<td>-53.5</td>
<td>-54.3</td>
</tr>
<tr>
<td>-7</td>
<td>-52.9</td>
<td>-53.8</td>
<td>-52.8</td>
<td>-54</td>
<td>-52.3</td>
</tr>
<tr>
<td>-6</td>
<td>-52.8</td>
<td>-51.6</td>
<td>-53.1</td>
<td>-55.4</td>
<td>-51.9</td>
</tr>
<tr>
<td>-5</td>
<td>-51.3</td>
<td>-51.4</td>
<td>-48.3</td>
<td>-52.5</td>
<td>-52.6</td>
</tr>
<tr>
<td>-4</td>
<td>-48.8</td>
<td>-49.4</td>
<td>-51.6</td>
<td>-49.4</td>
<td>-52.4</td>
</tr>
<tr>
<td>-3</td>
<td>-47.7</td>
<td>-50.9</td>
<td>-50.3</td>
<td>-48.9</td>
<td>-52.4</td>
</tr>
<tr>
<td>-2</td>
<td>-45.7</td>
<td>-44.2</td>
<td>-44</td>
<td>-45.1</td>
<td>-46.2</td>
</tr>
<tr>
<td>-1.5</td>
<td>-43.2</td>
<td>-41.5</td>
<td>-43.7</td>
<td>-41.5</td>
<td>-42.8</td>
</tr>
<tr>
<td>-1.375</td>
<td>-39.8</td>
<td>-39.9</td>
<td>-42</td>
<td>-42.5</td>
<td>-42.1</td>
</tr>
<tr>
<td>-1.25</td>
<td>-40.2</td>
<td>-38.1</td>
<td>-38.7</td>
<td>-39.3</td>
<td>-40.4</td>
</tr>
<tr>
<td>-1.125</td>
<td>-37.7</td>
<td>-39.1</td>
<td>-38.6</td>
<td>-36.5</td>
<td>-39.6</td>
</tr>
<tr>
<td>-1</td>
<td>-35.9</td>
<td>-39.3</td>
<td>-37.4</td>
<td>-36.7</td>
<td>-38</td>
</tr>
<tr>
<td>-0.875</td>
<td>-34.8</td>
<td>-37.3</td>
<td>-34.5</td>
<td>-36.2</td>
<td>-37</td>
</tr>
<tr>
<td>-0.75</td>
<td>-33.4</td>
<td>-33.3</td>
<td>-33.1</td>
<td>-32.7</td>
<td>-34.5</td>
</tr>
<tr>
<td>-0.625</td>
<td>-30.1</td>
<td>-32.4</td>
<td>-30.6</td>
<td>-33.3</td>
<td>-33.9</td>
</tr>
<tr>
<td>-0.5</td>
<td>-28.1</td>
<td>-27.7</td>
<td>-27.4</td>
<td>-29</td>
<td>-28.7</td>
</tr>
<tr>
<td>-0.375</td>
<td>-24.1</td>
<td>-23.7</td>
<td>-25.9</td>
<td>-27.1</td>
<td>-28.6</td>
</tr>
<tr>
<td>-0.25</td>
<td>-18.8</td>
<td>-19.9</td>
<td>-20.1</td>
<td>-20.7</td>
<td>-23.1</td>
</tr>
<tr>
<td>-0.187</td>
<td>-13.9</td>
<td>-13.9</td>
<td>-15.6</td>
<td>-17.1</td>
<td>-18.5</td>
</tr>
<tr>
<td>-0.125</td>
<td>-2.8</td>
<td>-7.3</td>
<td>-10.1</td>
<td>-10.9</td>
<td>-10.2</td>
</tr>
<tr>
<td>-0.062</td>
<td>3.3</td>
<td>1.8</td>
<td>-0.6</td>
<td>2</td>
<td>2.3</td>
</tr>
<tr>
<td>0</td>
<td>3.5</td>
<td>4</td>
<td>4</td>
<td>4.2</td>
<td>3.8</td>
</tr>
</tbody>
</table>

.. 165..
### Table 26: Pipe 1 Data

<table>
<thead>
<tr>
<th>FREQ</th>
<th>LOT1</th>
<th>L2T7</th>
<th>L5T5</th>
<th>L7T2</th>
<th>L1T0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.062</td>
<td>-3.5</td>
<td>-1.3</td>
<td>1.2</td>
<td>-4.7</td>
<td>-5.9</td>
</tr>
<tr>
<td>0.125</td>
<td>-13.1</td>
<td>-10.8</td>
<td>-9.4</td>
<td>-16.3</td>
<td>-17.7</td>
</tr>
<tr>
<td>0.187</td>
<td>-18.5</td>
<td>-19.3</td>
<td>-19.1</td>
<td>-19</td>
<td>-22.9</td>
</tr>
<tr>
<td>0.25</td>
<td>-22.9</td>
<td>-23.3</td>
<td>-22.8</td>
<td>-22.3</td>
<td>-23.8</td>
</tr>
<tr>
<td>0.375</td>
<td>-27</td>
<td>-24.9</td>
<td>-24.4</td>
<td>-29.3</td>
<td>-32</td>
</tr>
<tr>
<td>0.5</td>
<td>-30.6</td>
<td>-31.8</td>
<td>-30.5</td>
<td>-31.1</td>
<td>-31.1</td>
</tr>
<tr>
<td>0.625</td>
<td>-31.4</td>
<td>-32</td>
<td>-30</td>
<td>-33.4</td>
<td>-34.1</td>
</tr>
<tr>
<td>0.75</td>
<td>-34.1</td>
<td>-32.1</td>
<td>-33.3</td>
<td>-34.8</td>
<td>-38.5</td>
</tr>
<tr>
<td>0.875</td>
<td>-35.1</td>
<td>-36.3</td>
<td>-32.4</td>
<td>-36.9</td>
<td>-38.8</td>
</tr>
<tr>
<td>1</td>
<td>-37.5</td>
<td>-38.6</td>
<td>-37</td>
<td>-37.9</td>
<td>-39.8</td>
</tr>
<tr>
<td>1.125</td>
<td>-37.9</td>
<td>-38.5</td>
<td>-39.8</td>
<td>-37.4</td>
<td>-41.3</td>
</tr>
<tr>
<td>1.25</td>
<td>-41</td>
<td>-38.5</td>
<td>-38.9</td>
<td>-43.1</td>
<td>-40.5</td>
</tr>
<tr>
<td>1.375</td>
<td>-41</td>
<td>-39.5</td>
<td>-43.6</td>
<td>-44.2</td>
<td>-43</td>
</tr>
<tr>
<td>1.5</td>
<td>-42</td>
<td>-41.1</td>
<td>-45.1</td>
<td>-42.5</td>
<td>-42.9</td>
</tr>
<tr>
<td>2</td>
<td>-45.6</td>
<td>-45</td>
<td>-45.1</td>
<td>-44.3</td>
<td>-45.9</td>
</tr>
<tr>
<td>3</td>
<td>-46.3</td>
<td>-49.6</td>
<td>-49.8</td>
<td>-48.8</td>
<td>-51.9</td>
</tr>
<tr>
<td>4</td>
<td>-51.9</td>
<td>-50.2</td>
<td>-50.6</td>
<td>-50.1</td>
<td>-54</td>
</tr>
<tr>
<td>5</td>
<td>-49.7</td>
<td>-53.9</td>
<td>-51.8</td>
<td>-50.6</td>
<td>-53.5</td>
</tr>
<tr>
<td>6</td>
<td>-54.2</td>
<td>-53.5</td>
<td>-53</td>
<td>-55.1</td>
<td>-51.6</td>
</tr>
<tr>
<td>7</td>
<td>-53.2</td>
<td>-53</td>
<td>-53.5</td>
<td>-56.5</td>
<td>-53.2</td>
</tr>
<tr>
<td>8</td>
<td>-55.1</td>
<td>-53</td>
<td>-55.6</td>
<td>-54.6</td>
<td>-52.8</td>
</tr>
<tr>
<td>9</td>
<td>-52.7</td>
<td>-56</td>
<td>-51.8</td>
<td>-54.2</td>
<td>-52.9</td>
</tr>
<tr>
<td>10</td>
<td>-50.8</td>
<td>-54</td>
<td>-53.2</td>
<td>-54</td>
<td>-54.9</td>
</tr>
</tbody>
</table>
APPENDIX 10

A-10 Flow Chart of Maple Program used to determine pipe circuit parameters.
APPENDIX II

A11.1 Pipe Outline and Dimensions used in calculations

<table>
<thead>
<tr>
<th>Dimension (mm)</th>
<th>Pipe 1</th>
<th>Pipe 2</th>
<th>Pipe 3</th>
<th>Pipe 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>569</td>
<td>274</td>
<td>132.5</td>
<td>67</td>
</tr>
<tr>
<td>h</td>
<td>179</td>
<td>171</td>
<td>149.3</td>
<td>154.8</td>
</tr>
<tr>
<td>D</td>
<td>11.16</td>
<td>6.14</td>
<td>4.2</td>
<td>2.6</td>
</tr>
<tr>
<td>d</td>
<td>1.1</td>
<td>0.65</td>
<td>0.65</td>
<td>0.4</td>
</tr>
<tr>
<td>w</td>
<td>32.44</td>
<td>24.14</td>
<td>11.15</td>
<td>7.5</td>
</tr>
<tr>
<td>R</td>
<td>47</td>
<td>31.15</td>
<td>17.31</td>
<td>9.36</td>
</tr>
<tr>
<td>r</td>
<td>6.85</td>
<td>5.1</td>
<td>3.6</td>
<td>2.6</td>
</tr>
<tr>
<td>t</td>
<td>1</td>
<td>.95</td>
<td>.5</td>
<td>.5</td>
</tr>
<tr>
<td>h + H</td>
<td>748</td>
<td>445</td>
<td>281.8</td>
<td>221.8</td>
</tr>
<tr>
<td>l</td>
<td>12</td>
<td>6</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>D'</td>
<td>8.85</td>
<td>4.8</td>
<td>3.5</td>
<td>1.9</td>
</tr>
</tbody>
</table>

A11.2 Pipe segments (*annotated diagram of pipe is overleaf*)
Appendices

Fig a10.2 Anatomy of the Organ Flue Pipe

Pipe Body

Pipe Foot

Toe/Foot Hole

Pipe mouth

Mouth Width

Mouth Height or Cut Up

Upper lip/edge

Upper Lip

Lower Lip

Windway

Languid

Languid Angle or Bevel

(θ)
APPENDIX 12

A-12 Manipulating the Wirelisting to Introduce a Turbulence(noise) input

Let N random variables with a Gaussian Distribution that have a mean $\mu$ and standard deviation $\sigma$ be required to simulated noise. Let in addition the N variables be required to be put in cell C1 say. The macro that realises this in MINITAB is:

```
RANDOM N C1;
GUASSIAN $\mu$ $\sigma$.
```

By using a $\mu$ of 1 and a $\sigma$ of 0.25, 0.75 and 1 gives simulated turbulence intensities of 25%, 50%, 75% and 100% respectively when the noise is combined with a sinusiodal signal ($\mu$) with input of 1V.

If the N random variables were $X_1$, $X_2$, $X_3$ ... $X_N$ say, then the input segment of the wirelisting programme generated by POWERVIEW for HSPICE simulation could be modified as the input in N time steps, $T_1$, $T_2$, $T_3$ ... $T_N$ to the corresponding variable.

As an example, if using the input pair of $X_N$ and $T_N$ in the wirelisting for Pipe 1 say, then the modified programme will become (modifications in bold):

```
* Project PIPEC
* Powerview Wirelist Created with Version 5.1.2
* Inifile : wspice.ini
* Options : -m -f -n -z -q -v -x
* Levels :

RT OUT N119 0.3
RO N164 N130 667.8
LO N130 0 0.001967
CT N119 0 19.2E-6
LIN N1107 OUT 0.0003603
RIN N164 N1107 .814
LPP OUT 0 0.00253789
CPP OUT 0 0.8112E-5
VIN N164 0 PWL ( $T_1$ $X_1$
+ $T_2$ $X_2$
+ $T_3$ $X_3$
+ ...
+ ...
+ $T_N$ $X_N$ )
.AC DEC 1000 1HZ 10KHZ
.PROBE AC VDB(OUT) VP(OUT)
.OPTIONS INGOLD=2 CSDF=2
.END
```
REFERENCES

Acronyms:  JASA:- J. Acoustical Society of America
JASJpn- J. Acoustical Society of Japan
JFM:- J. Fluid Mechanics
JSV:- J. Sound & Vibration
ASME:- American Society of Mechanical Engineers.

1 Agullo J, Barjau A, & Martinez J
Alternatives to the impulse response to describe the acoustical behaviour of conical ducts.
JASA 1988 84(5) 1606-1612

2 Andersen Poul-Gerhard
Organ building and design
George Allen & Unwin Ltd., 1976, ch5

3 Angster J & Miklos A
New developments on the understanding of the buildup of organ sounds.
13th Int. Congress on Acoustics, Yugoslavia 1989, 99-102

4 Audsley G A
The art of organ building vol II
Dover Publications, 1965, ch. XLV

5 Benade A. H.
Relation of air column resonances to sound spectra produced by wind instruments.
JASA 1966 40(1) 247-249

6 Bendat J S & Piersol A C
Engineering applications of correlation and spectral analysis.
John Wiley 1980 Ch 1-3.

7 Bradshaw A P
An introduction to turbulence and its measurements.
Pergamon Press, 1971

8 Bruggeman J C, Hirsberg A et al
Self Sustained aeroacoustics pulsations in gas transport systems: experimental study of the influence of closed side branches.
JSV, 1991, 150(3) 371-393
<table>
<thead>
<tr>
<th></th>
<th>Author(s)</th>
<th>Title</th>
<th>Journal/Book Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Caddy R S &amp; Pollard H F</td>
<td>Transient sounds in organ pipes</td>
<td>ACUSTICA 1957 v7 277-280</td>
</tr>
<tr>
<td>10</td>
<td>Cargill A M</td>
<td>Low-frequency sound radiation and generation due to the interaction of unsteady flow with a pipe jet.</td>
<td>JFM 1982 v121 59-105</td>
</tr>
<tr>
<td>11</td>
<td>Coltman J W</td>
<td>Sounding mechanism of the flute &amp; organ pipe</td>
<td>JASA 1968 44(4) 983-992</td>
</tr>
<tr>
<td>12</td>
<td>Coltman J W</td>
<td>Sound radiation from the mouth of an organ pipe</td>
<td>JASA 1969 46(2) II 477-??</td>
</tr>
<tr>
<td>13</td>
<td>Coltman J W</td>
<td>Jet drive mechanisms in edge tones and organ pipes.</td>
<td>JASA 1976 60(3) 725-733</td>
</tr>
<tr>
<td>14</td>
<td>Coltman J W</td>
<td>Momentum transfer in jet excitation of flute-like instruments</td>
<td>JASA 1981 69(4) 1164-1168</td>
</tr>
<tr>
<td>15</td>
<td>Coltman J W</td>
<td>Time domain simulation of the flute</td>
<td>JASA 1992 92(1) 69-73</td>
</tr>
<tr>
<td>16</td>
<td>Coltman J W</td>
<td>Private Communication, 1993</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Cremer, von L &amp; Ising H</td>
<td>Die selbsterregten schwingungen von orgelpfeifen (The self-excited vibrations of organ pipes)</td>
<td>ACUSTICA 1968 19 143-153</td>
</tr>
<tr>
<td>19</td>
<td>Diehl, G M</td>
<td>Machinery Acoustics</td>
<td>John Wiley &amp; Sons, 1973</td>
</tr>
<tr>
<td>Reference</td>
<td>Author(s)</td>
<td>Title</td>
<td>Source</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
<td>-------</td>
<td>--------</td>
</tr>
<tr>
<td>20</td>
<td>Disselhorst JHM &amp; Wijngaarden L Van</td>
<td>Flow in the exit of open pipes during acoustic resonance</td>
<td>JFM 1980 99(2) 293-319</td>
</tr>
<tr>
<td>22</td>
<td>Elder S A</td>
<td>On the mechanism of sound production in organ pipes.</td>
<td>JASA 1973 54(6) 1554-1564</td>
</tr>
<tr>
<td>23</td>
<td>Elder S A</td>
<td>Private Communication, 1993</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Elvin L</td>
<td>Organ blowing: its history and development.</td>
<td>Laurence Elvin Pub., 1971</td>
</tr>
<tr>
<td>26</td>
<td>Fabre, B; Hirscberg et al</td>
<td>Jet drive and edgetone in flue organ pipes.</td>
<td>Submitted to JASA, 1993</td>
</tr>
<tr>
<td>27</td>
<td>Finch, T.L. &amp; Nolle A. W.</td>
<td>Pressure wave reflections in an organ note channel</td>
<td>JASA, 1986, 79(5) 1584-1591</td>
</tr>
<tr>
<td>28</td>
<td>Fletcher H, Blackham B D &amp; Christensen DA</td>
<td>Quality of organ tones</td>
<td>JASA, 1963 vol 35(3), 314-325</td>
</tr>
<tr>
<td>29</td>
<td>Fletcher, N. H.</td>
<td>Nonlinear interactions in organ flue pipes.</td>
<td>JASA 1974, vol 56(2), 645-652</td>
</tr>
<tr>
<td>30</td>
<td>Fletcher, N. H.</td>
<td>Jet-drive mechanism in organ pipes</td>
<td>JASA, 1976, 60(2) 481-483</td>
</tr>
<tr>
<td>Reference</td>
<td>Author(s)</td>
<td>Title</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Fletcher, N. H.</td>
<td>Mode locking in nonlinearly excited inharmonic musical oscillators. JASA, 1978, 64(6), 1566-1569</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Fletcher, N. H.</td>
<td>Private Communication, 1993</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>Fletcher, N. H. &amp; Thwaites S</td>
<td>Wave propagation on an acoustically perturbed jet. ACUSTICA 1979, v42 323-334</td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>Gueritey P M</td>
<td>Reflexions et observations sur les souffleries ISO Year Book, 1992, 64-91</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>Helmholz, Herman L.F.</td>
<td>On the sensations of tone as a physiological basis for the theory of music Longmans, Green &amp; Co, 1885, Ch v - Sectn. 5-6, 88-102</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>Hinze, J O</td>
<td>Turbulence McGraw Hill 1975, ch 1 &amp; 2</td>
<td></td>
</tr>
</tbody>
</table>
42 Hirscberg A et al
A quasi-stationary model of air flow in the reed channel of single reed woodwind instruments.
ACUSTICA, 1990, v70, 146-154

43 Hirscberg A.
Some fluid dynamic aspects of speech
Bulletin de la communication parlee, 1992, v2, 7-30

44 Hopkins E.J. & Rinbault E. T.
The organ: its history and construction
Frits Knuf, Holland, 1965

45 Horowitz and Hill
The Art of Electronics

46 Howe M.S.
On the absorption of sound by turbulence and other hydrodynamic flows.

47 HSPICE
HSPICE User's Manual H9001
Meta-Software, 1990

48 Jarvis E K
Private Communication 1992

49 Kergomard, J.
Tone hole external interactions in woodwinds musical instruments.
13th Int. Congress. on Acoustics, Yugoslavia, 1989, 53-56

50 Lighthill, James
Waves in Fluids
Camb. Univ. Press., 1979 (Ch-1)

51 Magnusson, S.
Die klaaglichen auswirkugen von balgphatenschwingungen (The tonal effects of bellow reverberation)
ISO Info. 1974, 827-830

52 Mahu, W.E.A Peters, M.C.A.M. et al
Attack transient of a flue organ pipe.
2nd Dutch conference on mechanics; Rolduc, Netherlands, 1992.

..175..
<table>
<thead>
<tr>
<th>Reference</th>
<th>Author(s)</th>
<th>Title</th>
<th>Journal</th>
<th>Volume</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>Martinez J &amp; Agullo J</td>
<td>Conical bores, Part II, multiconvolution.</td>
<td>JASA</td>
<td>1988, 84(5)</td>
<td>1620-1627</td>
</tr>
<tr>
<td>59</td>
<td>Mebold H P</td>
<td>Uberlegungen zum orgelwind; der offene wind (considerations about the organ wind supply - the open wind)</td>
<td>ISO Info</td>
<td>1989, v30</td>
<td>11-24</td>
</tr>
<tr>
<td>60</td>
<td>Mercer, DMA</td>
<td>The voicing of organ flue pipes</td>
<td>JASA</td>
<td>1951, 23(1)</td>
<td>45-54</td>
</tr>
<tr>
<td>62</td>
<td>Morrison, R</td>
<td>Hi-tech digital organ hit all the right notes</td>
<td>“The Times” (UK), Feb 4, 1995</td>
<td>No. 65182</td>
<td></td>
</tr>
</tbody>
</table>

..176..
<table>
<thead>
<tr>
<th>Reference</th>
<th>Author(s)</th>
<th>Title</th>
<th>Publication Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>Morse P.M.</td>
<td>Vibration and sound</td>
<td>McGraw Hill, 1948, Ch 6- Sd Prop in tubes, Ch 7, sound transmission through ducts, ch 2, coupled oscillations.</td>
</tr>
<tr>
<td>64</td>
<td>Narasimha, R &amp; Sreenivasan K R</td>
<td>Relaminarisation of fluid flows.</td>
<td>Advances in Applied Mechanics, 1979, v9, 221-309</td>
</tr>
<tr>
<td>65</td>
<td>National Physical Lab.</td>
<td>Turbulence measurements with hot wire anemometers.</td>
<td>Notes on applied sciences, #33</td>
</tr>
<tr>
<td>68</td>
<td>Nisenfeld, A.E.</td>
<td>Centrifugal compressors.</td>
<td>ISA Monograph Series, 1982, #3: Ch-1 &amp; 3</td>
</tr>
<tr>
<td>70</td>
<td>Norman H &amp; Norman HJ</td>
<td>The organ today</td>
<td>Barrie &amp; Rockliff Pub., 1967</td>
</tr>
<tr>
<td>71</td>
<td>Papoullis A</td>
<td>Circuits and Systems, a modern approach</td>
<td>Holt, Rinehart &amp; Winston 1980, Ch5</td>
</tr>
<tr>
<td>72</td>
<td>Peters, MCAM et al</td>
<td>Damping and reflection coefficient measurements for an open pipe at low Mach and low Helmholtz numbers.</td>
<td>Technical Univ. of Eindhoven, April 1993</td>
</tr>
<tr>
<td>75</td>
<td>Praet, W. et al.</td>
<td>Organ dictionary CEOS v.z.w. Zwijndrecht, Belgium, 1989</td>
<td></td>
</tr>
<tr>
<td>76</td>
<td>Rienstra, S.W.</td>
<td>A small Strouhal number analysis for acoustic wave-jet flow-pipe interaction. JSV, 1983, 86(4) 539-556</td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>Rosenhouse, G</td>
<td>Acoustic wave propagation in bent thin walled wave guides. JSV, 1970, 67(4) 469-486</td>
<td></td>
</tr>
<tr>
<td>79</td>
<td>Ryan, B, Joiner, BL &amp; Ryan, TA</td>
<td>Minitab Handbook Duxbury Press, 1985</td>
<td></td>
</tr>
</tbody>
</table>

..178..
<table>
<thead>
<tr>
<th>Reference</th>
<th>Author(s)</th>
<th>Title</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>Sreenivasan K R &amp; Strykowski P J</td>
<td>Stabilization effects in flow through helically coiled pipes.</td>
<td>Expts. in Fluids, 1983, 1, 31-36</td>
</tr>
<tr>
<td>87</td>
<td>Stephens RWB &amp; Bate AE</td>
<td>Acoustics and vibrational physics</td>
<td>Edward Arnols Pubs. Ltd., 1966, ch17:</td>
</tr>
<tr>
<td>90</td>
<td>Thwaites S &amp; Fletcher N H</td>
<td>Wave propagation on turbulent jets.</td>
<td>ACUSTICA, 1980, 45, 175-179</td>
</tr>
<tr>
<td>91</td>
<td>Thwaites S &amp; Fletcher N H</td>
<td>Acoustic admittance of organ pipe jets.</td>
<td>JASA, 1983, 74(2), 400-408.</td>
</tr>
<tr>
<td>92</td>
<td>TSI</td>
<td>TSI Instruction Manual</td>
<td>CTA Model 1750, April 1988</td>
</tr>
<tr>
<td>93</td>
<td>Verge, M P, Fabre B et al</td>
<td>Jet formation and jet velocity fluctuations in a flue organ pipe.</td>
<td>Submitted to JASA, 1993</td>
</tr>
</tbody>
</table>
95  Viswanath P R, Narasimha R & Prabhu A
    Visualization of relaminarizing flows.
    J. Indian Inst. of Science, 1978, 159-165

96  Wagner, G D
    The problem of organ wind from an organist view point.
    ISO Info, 1989, 30, 24-30

97  Wonnacolt T H & Wonnacolt R J
    Introductory Statistics

98  Yoshikawa S & Saneyosh J
    Feedback excitation mechanism in organ pipes.
    JASJpn, 1980, E1(3) 175-191

99  Impeller configuration of the blower was designed by Prof H V Rao, and constructed
    by P J Norman both of the School of Engineering, University of Huddersfield

100 Maple V Release 2 is a scientific computer programming package designed in Canada.
    The ref. text used was: First Leaves: A Tutorial Introduction to
        Maple V, by Char B W et al; Springer-Verlag, 1992

101 Wireless World, May 1978, p70

102 Collins, Peter
    Peter Collins Organ Builders, Melton Mowbray, Leicestershire,
    UK. Independent observation.

103 Davies, P.O.A.L
    Flow-acoustic coupling in ducts
    JSV, 1981, 77(2), 191-209

104 Ramakrishnan, R & Davies P.O.A.L.
    Sound generation by flow-acoustic coupling
    In Mechanics of Sound Generation in Flows,
    E-A Muller, Editor; Springer-Verlag, 1979,62-68.