# Leak Detection and Condition Assessment for Water Distribution Pipelines using Fluid Transient Waves

**Jinzhe Gong**
B.Eng., M.Eng.

Thesis submitted in fulfilment of the requirements for the degree
of Doctor of Philosophy

The University of Adelaide
Faculty of Engineering, Computer and Mathematical Sciences
School of Civil, Environmental and Mining Engineering

*To my beloved wife He Shi and son Keming Gong*

# Abstract

The focus of this PhD research is to develop non-invasive and cost-effective techniques for assessing the structural condition of pressurised pipelines using fluid transient pressure waves. The specific objectives include the detection of leaks and localised deterioration that is distributed along a pipeline, such as extended sections of corrosion or the spalling of cement lining. The latter is described by *pipeline condition assessment* in this thesis.

The transient behaviour of a leak is studied in the frequency domain. Numerical studies conducted in this research demonstrate that two leak-induced patterns (on the resonant and the anti-resonant responses) can exist in a frequency response diagram (FRD). The amplitudes of the responses are related to the impedance of the valve in a reservoir-pipeline-valve (RPV) system.

A new leak detection technique has been developed in this research based on the further understanding of the leak-induced patterns. This technique uses the relative sizes of the first three resonant responses to determine the location and size of a single leak in RPV systems. In reservoir-pipeline-dead end systems, the information required for single event leak detection is further reduced to the first two resonant responses.

A new measurement strategy for the extraction of the FRD of single pipelines is proposed in this research. The boundary valve loss is used to adjust the amplitude of the leak-induced pattern on the resonant responses and also the sharpness of the resonant peaks. A specific type of pseudo-random binary sequence (PRBS) termed the inverse repeat sequence (IRS), is used as the excitation signal. The antisymmetric property of IRS enables part of the nonlinear responses of the system under excitation to be cancelled out, yielding a measured FRD close to the theoretical linear system response. A side-discharge valve based transient generator is designed and fabricated in this research to implement the new FRD measurement strategy. Laboratory experiments are conducted on an intact pipeline and a pipeline with a leak.

This research also conducts analysis of the characteristics of distributed pipe wall deterioration and develops new detection techniques. In a measured pressure trace, the size of the reflection resulting from a section of pipeline with a change in wall thickness is indicative of the characteristic impedance of this section. Once the impedance of this section is determined, the wave speed and wall thickness can be estimated. A technique for the detection of a single deteriorated section in pipelines is developed based on the above analysis.

Two other condition assessment techniques are developed to deal with the complexities induced by multiple deteriorated sections. The first technique is termed *reconstructive MOC* (method of characteristics) *analysis*, which uses the pressure trace measured at the upstream face of the valve in a RPV system to determine the distribution of the impedance along the pipeline. The algorithm reconstructs a MOC grid by calculating the MOC compatibility equations backwards in time, estimating the properties of the pipeline (impedance, wave speed) and the length of each pipe reach as discretised by the MOC grid from the valve towards the reservoir. Preliminary experimental verification is conducted to verify the applicability of the new technique.

The second technique is *reconstructive transient analysis* (RTA), which can be conducted at any interior accessible points along a pipeline, and does not require a RPV boundary condition. The RTA uses two pressure transducers in close proximity to measure two transient pressure traces in one test. A signal processing algorithm is developed to extract the directional transient waves (traveling upstream and downstream). The use of the directional transient waves enables the step response function (SRF) of the section of pipe upstream or downstream of the paired pressure transducers to be obtained. The *reconstructive MOC analysis* is then adapted to interpret the SRF to yield the distribution of the impedance, from which the location and severity of distributed deterioration can be identified.

# Statement of Originality

I, *Jinzhe Gong*, hereby declare that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution in my name and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

The author acknowledges that copyright of published works contained within this thesis resides with the copyright holder(s) of those works.

I also give permission for the digital version of my thesis being made available on the web, via the University's digital research repository, the Library catalogue, the Australian Digital Thesis Program (ADTP) and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Signed: ..................................................... Date: ......................

# Acknowledgments

First of all, I would like to show my gratitude to my supervisors, Prof. Martin Lambert, Prof. Angus Simpson and Dr. Aaron Zecchin. This PhD thesis would not be possible without their guidance and support. They have reviewed all my manuscripts and given comments for improvement. They also provided financial support to me for attending international conferences.

I gratefully acknowledge the support from Ms. Barbara Brougham. She has given me many helpful advices on academic writing. She helped me gain not only skills but also confidence in writing academic papers.

I would like to thank technicians Brenton Howie, Simon Order and Stan Woithe in the Robin Hydraulics Laboratory at the University of Adelaide. They provided support throughout my laboratory experiments, especially for the design and fabrication of the customised transient signal generator used in my research.

I thank all my fellow postgraduate students within the School for keeping company and sharing experiences with me. I also thank all the staff in the School of Civil, Environmental and Mining Engineering for their support and help over the years of my PhD study.

I would like to thank the emotional and financial support from my parents, Mr. Qi Gong and Ms. Jinying Zhang. I greatly appreciate my wife, He Shi, for her unwavering support and encouragement since we were married. Lastly, I thank my baby boy, Keming, who brought me joy and hope.

# Table of Contents

**Abstract** .......... v

**Statement of Originality** .......... vii

**Acknowledgments** .......... ix

**Table of Contents** .......... xi

**List of Publications** .......... xix

Journal papers .......... xix
Conference papers .......... xxi

**List of Tables** .......... xxiii

**List of Figures** .......... xxv

**1. Introduction** .......... 1
1.1 Research background .......... 1
1.1.1 Significance of leak detection and condition assessment for water pipelines .......... 1
1.1.2 Limitations in current technologies .......... 3
1.1.3 Leak detection and wall condition assessment using fluid transient waves .......... 4
1.2 Research aims .......... 10
1.3 Organisation of thesis .......... 13

**2. Synopsis of Publications** .......... 15
2.1 Journal paper 1 .......... 15
2.2 Journal paper 2 .......... 16
2.3 Journal paper 3 .......... 17
2.4 Journal paper 4 .......... 18
2.5 Journal paper 5 .......... 19
2.6 Journal paper 6 .......... 20

2.7 Journal paper 7 .......... 21
2.8 Journal paper 8 .......... 22
2.9 Journal paper 9 .......... 23

**3. Frequency Response Diagram for Pipeline Leak Detection: Comparing the Odd and the Even Harmonics (Journal Publication 1) .......... 27**

Statement of Authorship .......... 29
3.1 Introduction .......... 33
3.2 Fundamental equations .......... 36
3.3 Frequency response equations for a leaking pipe .......... 38
3.4 Dimensionless analysis of the leak-induced patterns .......... 40
  3.4.1 Dimensionless analysis of frictionless leaking pipes .......... 40
  3.4.2 Impedance parameter ranges .......... 42
  3.4.3 Leak size derivation .......... 44
3.5 Dimensionless modeling of frictionless leaking pipes .......... 45
3.6 Case study of a specific pipeline with steady friction .......... 49
3.7 Comparison of the two existing leak detection methods .......... 55
3.8 Challenges to current FRD-based leak detection techniques .......... 56
  3.8.1 Summary of the assumptions .......... 57
  3.8.2 Challenges in practical applications .......... 58
3.9 Conclusions .......... 61

**4. Single Event Leak Detection in a Pipeline using the First Three Resonant Responses (Journal Publication 2) .......... 65**

Statement of Authorship .......... 67
4.1 Introduction .......... 71
4.2 Frequency response equations for a single pipe with a leak .......... 75
  4.2.1 System configurations .......... 75
  4.2.2 Frequency response equations for RPV-High Loss Valve systems .......... 76
  4.2.3 Frequency response equations for RPV-Closed Valve systems . 79
  4.2.4 Comparison between the RPV-High Loss Valve and the RPV-Closed Valve boundary conditions .......... 80

- 4.3 Leak detection for *RPV-High Loss Valve* systems .......... 81
  - 4.3.1 Determination of the leak location for RPV-High Loss Valve systems .......... 82
  - 4.3.2 Determination of the leak size for RPV-High Loss Valve systems .......... 83
  - 4.3.3 Sensitivity analysis for the three resonant responses-based leak location algorithm .......... 84
- 4.4 Leak detection for *RPV-Closed Valve* systems .......... 89
  - 4.4.1 Determination of the leak location for RPV-Closed Valve systems .......... 90
  - 4.4.2 Determination of the leak size for RPV-Closed Valve systems .. 91
  - 4.4.3 Sensitivity analysis for the two resonant responses-based leak location algorithm .......... 92
- 4.5 Numerical verification .......... 94
  - 4.5.1 Unsteady friction model .......... 94
  - 4.5.2 Case study .......... 96
  - 4.5.3 Simulations for various leak locations .......... 98
- 4.6 Experimental verification .......... 100
  - 4.6.1 System configuration and experimental data .......... 100
  - 4.6.2 Leak location using the three resonant responses-based technique .......... 101
  - 4.6.3 Leak location and size estimation using the two resonant responses-based technique .......... 101
  - 4.6.4 Summary of experimental verification .......... 102
- 4.7 Challenges in field applications .......... 102
- 4.8 Conclusions .......... 103

**5. Determination of the Linear Frequency Response of Single Pipelines using Persistent Transient Excitation: a Numerical Investigation (Journal Publication 3) .......... 109**

- Statement of Authorship .......... 111
- 5.1 Introduction .......... 115
- 5.2 Nonlinearities of a pipeline system and linearisation in FRD-based leak detection techniques .......... 117

5.3 Selection of appropriate excitation signals to minimise the nonlinear response of a pipeline ........ 121
5.4 Comparison of the MLBS and the IRS in the accuracy of linear FRD extraction ........ 124
5.5 Conclusions ........ 128

**6. A Customized Side-Discharge Valve for Extracting the Frequency Response Function of Hydraulic Pipelines using Pseudorandom Binary Signals (Journal Publication 4) ........ 131**
Statement of Authorship ........ 133
6.1 Introduction ........ 137
6.2 Experimental apparatus ........ 140
6.3 Experimental extraction of the linear FRF using MLBS and IRS ........ 142
  6.3.1 Case study No.1: For an amplitude of input signal of $A_{in} \approx 0.5$ 144
  6.3.2 Case study No.2: For an amplitude of input signal of $A_{in} \approx 0.2$ 147
  6.3.3 Case study No.3: For an amplitude of input signal of $A_{in} \approx 0.06$ ........ 150
6.4 Conclusions ........ 153

**7. Single Event Leak Detection in a Pipeline using Fluid Transients with Inverse-Repeat Binary Sequences (Journal Publication 5) ........ 157**
Statement of Authorship ........ 159
7.1 Introduction ........ 163
7.2 Effects of boundary valve loss on the shape of the frequency response diagram ........ 166
  7.2.1 RPV-Open Valve configuration ........ 167
  7.2.2 RPV-Closed Valve configuration ........ 169
  7.2.3 RPV-High Loss Valve configuration ........ 171
7.3 Appropriate values of valve impedance for leak detection ........ 172
7.4 Extraction of the FRD of a pipe with a leak using a dual-solenoid controlled side-discharge valve and inverse-repeat sequences ........ 175
7.5 Estimation of the location and impedance of the leak using the three resonant responses-based technique ........ 179
7.6 Conclusions ........ 182

**8. Detection of Distributed Deterioration in Single Pipes Using Transient Reflections (Journal Publication 6) .................................187**

Statement of Authorship ............................................................................189

8.1 Introduction ..........................................................................................193

8.2 Background ..........................................................................................194

8.3 Wave propagation analysis ................................................................195

8.4 Distributed deterioration detection procedures ...................................198

8.4.1 Detection at the end of a pipeline ..............................................198

8.4.2 Detection at an interior location ................................................201

8.5 Distributed versus discrete deterioration ...........................................203

8.6 Experimental verification ...................................................................203

8.6.1 System configuration ................................................................203

8.6.2 Experimental pressure traces ....................................................205

8.6.3 Determination of the impedance, wave speed and wall thickness ..........................................................................................206

8.6.4 The influence of the initial wave front ......................................212

8.6.5 Determination of the location and length ..................................218

8.7 Conclusions .........................................................................................219

**9. Detection of Extended Structural Deterioration in a Pipeline using Fluid Transients: a Sensitivity Analysis (Journal Publication 7)....221**

Statement of Authorship ............................................................................223

9.1 Introduction ..........................................................................................227

9.2 Pipeline impedance and wave speed ..................................................229

9.3 Transient wave reflection and transmission .......................................229

9.4 Sensitivity analysis of the effects of a change in wall thickness on the size of the transmitted and reflected waves .......................................232

9.4.1 An internal change in wall thickness .........................................233

9.4.2 An external change in wall thickness ........................................238

9.5 Conclusions .........................................................................................241

**10. Detection of Localized Deterioration Distributed along Single Pipelines by Reconstructive MOC Analysis (Journal Publication 8) ...........................................................................................245**

Statement of Authorship ........ 247
10.1 Introduction ........ 251
10.2 Method of characteristics ........ 254
10.3 Reconstructive MOC analysis ........ 256
10.3.1 Previous research on performing MOC analysis backwards in time ........ 256
10.3.2 Problem definition ........ 257
10.3.3 Assumptions ........ 259
10.3.4 Analysis for the first reach ........ 260
10.3.5 Analysis for the second reach ........ 262
10.3.6 Analysis for the subsequent pipeline reaches ........ 265
10.4 Numerical simulations ........ 266
10.5 Experimental verification ........ 269
10.5.1 Experimental pipeline configuration ........ 270
10.5.2 Experimental pressure trace ........ 271
10.5.3 Preprocessing of the measured data ........ 272
10.5.4 Reconstructive MOC analysis for the step response function .. 274
10.6 Conclusions ........ 277

**11. Condition Assessment of Hydraulic Pipelines using Paired Pressure Transducers and Reconstructive Transient Analysis (Journal Publication 9) ........ 281**
Statement of Authorship ........ 283
11.1 Introduction ........ 287
11.2 Measurement of transient pressure traces ........ 291
11.2.1 Pipeline configuration ........ 291
11.2.2 Pressure measurement ........ 292
11.3 Extraction of the reflected axial plane waves ........ 293
11.3.1 Expression of the measured pressure traces ........ 293
11.3.2 Estimation of the axial plane waves ........ 294
11.4 Determination of the unit step response function ........ 295
11.5 Reconstructive transient analysis ........ 297
11.5.1 Transient wave behavior in pipes with a deteriorated section .. 297
11.5.2 Implementation of reconstructive transient analysis ........ 299

11.6 Numerical simulations ........ 305

11.6.1 System configuration ........ 305

11.6.2 Pressure traces from MOC modeling ........ 306

11.6.3 Determination of the axial plane waves ........ 307

11.6.4 Determination of the unit step response function ........ 309

11.6.5 Determination of the impedance and wave speed using RTA .. 310

11.6.6 Effects of friction ........ 311

11.7 Conclusions ........ 312

**12. Conclusions ........ 317**

12.1 Research contributions ........ 318

12.2 Research limitations and future work ........ 320

**References ........ 323**

# List of Publications

## Journal papers

The following peer-reviewed journal papers are the major outcomes of this research and they form the main body of this thesis.

1. Gong, J., Zecchin, A. C., Simpson, A. R., and Lambert, M. F. (2013). "Frequency response diagram for pipeline leak detection: comparing the odd and the even harmonics." *Journal of Water Resources Planning and Management*, DOI: 10.1061/(ASCE)WR.1943-5452.0000298 (accepted for publication).

2. Gong, J., Lambert, M. F., Simpson, A. R., and Zecchin, A. C. (2013). "Single event leak detection in a pipeline using the first three resonant responses." *Journal of Hydraulic Engineering*, 139(6), 645-655.

3. Gong, J., Simpson, A. R., Lambert, M. F., and Zecchin, A. C. (2013). "Determination of the frequency response diagram of single pipelines using persistent transient excitation: a numerical investigation." *Journal of Hydraulic Research*, DOI: 10.1080/00221686.2013.818582 (accepted for publication).

4. Gong, J., Lambert, M. F., Simpson, A. R., and Zecchin, A. C. (2013). "A customized side-discharge valve for extracting the frequency response function of hydraulic pipelines using pseudorandom binary signals." *Journal of Hydraulic Engineering* (under review).

5. Gong, J., Lambert, M. F., Simpson, A. R., and Zecchin, A. C. (2013). "Single event leak detection in a pipeline using fluid transients with inverse-repeat binary sequences." *Journal of Hydraulic Engineering*, (under review).

6. Gong, J., Simpson, A. R., Lambert, M. F., Zecchin, A. C., Kim, Y., and Tijsseling, A. S. (2013). "Detection of distributed deterioration in single pipes using transient reflections." *Journal of Pipeline Systems Engineering and Practice*, 4(1), 32-40.

7. Gong, J., Simpson, A. R., Zecchin, A. C. and Lambert, M. F. (2013). "Detection of extended structural deterioration in a pipeline using fluid transients: a sensitivity analysis." *Journal of Hydraulic Engineering*, (under review).

8. Gong, J., Lambert, M. F., Simpson, A. R., and Zecchin, A. C. (2013). "Detection of localized deterioration distributed along single pipelines by reconstructive MOC analysis." *Journal of Hydraulic Engineering*, DOI: 10.1061/(ASCE)HY.1943-7900.0000806 (accepted for publication).

9. Gong, J., Zecchin, A. C., Lambert, M. F., and Simpson, A. R. (2013). "Condition assessment of hydraulic pipelines using paired pressure transducers and reconstructive transient analysis." *Journal of Hydraulic Engineering* (under review).

# Conference papers

The following conference papers are also outcomes of this research.

1. Gong, J., Lambert, M. F., Simpson, A. R., and Zecchin, A. C. (2012). "Distributed deterioration detection in single pipelines using transient measurements from pressure transducer pairs." In: *11th International Conference on Pressure Surges*, 24-26 October 2012, Lisbon, Portugal. Cranfield, UK: BHR Group, 2012: 127-140.

2. Gong, J., Lambert, M. F., Simpson, A. R., and Zecchin, A. C. (2012). "Distributed deterioration detection and location in single pipes using the impulse response function." In: WDSA 2012: *14th Water Distribution Systems Analysis Conference,* 24-27 September 2012, Adelaide, South Australia. Barton, ACT, Australia: Engineers Australia, 2012: 702-719.

3. Gong, J., Zecchin, A. C., Lambert, M. F., and Simpson, A. R. (2012). "Signal separation for transient wave reflections in single pipelines using inverse filters." In: *World Environmental and Water Resources Congress 2012: Crossing Boundaries*, 20-24 May 2012, Albuquerque, New Mexico. Reston, VA: ASCE, 2012: 3275-3284.

4. Gong, J., Simpson, A. R., Lambert, M. F., Zecchin, A. C., and Kim, Y. (2011). "Detection of distributed deteriorations in single pipes using transient reflections." In: ICPTT 2011: *International Conference on Pipelines and Trenchless Technology 2011*, 26-29 October 2011, Beijing China. (Presented in the conference but not included in the conference proceedings. Published as Journal Paper No.6 after a major revision.)

5. Gong, J., Lambert, M. F., Zecchin, A. C., and Simpson, A. R. (2011). "Frequency response measurement of pipelines by using inverse-repeat binary sequences." In: CCWI 2011: *Computing and Control for the Water Industry 2011: Urban Water Management - Challenges and Opportunities*, 5-7 September, 2011, the University of Exeter, Exeter, UK. Exeter, UK: the University of Exeter, 2011: 883-888.

# List of Tables

Table 3.1 System parameters for the case study ............................................49

Table 4.1 System parameters for the numerical simulations...........................96

Table 7.1 Experimental results for leak location and size estimation. ..........181

Table 8.1 Impedance $B_1$, wave speed $a_1$ and wall thickness $e_1$ of the deteriorated section.......................................................................209

Table 8.2 Difference in the impedance, wave speed and wall thickness between the deterioration and the original pipeline .....................211

Table 8.3 Magnitude of the reflected disturbance and the estimated impedance difference between the deterioration and the original pipeline ....216

Table 8.4 Location and length of the deteriorated section ............................219

Table 10.1 Estimated properties of the deteriorated section and corresponding error ........................................................................................275

# List of Figures

Figure 1.1 Research aims and their hierarchy ................................................12

Figure 2.1 Contribution of the nine journal publications presented in this thesis in relation to the research aims of this doctoral research .....25

Figure 3.1 A reservoir-pipeline-valve system with a leak..............................38

Figure 3.2 A dimensionless FRD with same leak-induced pattern amplitudes at the odd and even harmonics for a frictionless pipe simulation ..45

Figure 3.3 Dimensionless leak-induced patterns at the odd and even harmonics (frictionless pipe). The circles are values at harmonics, and the solid lines are the sinusoidal fitted lines ............................46

Figure 3.4 Variation of the leak-induced pattern amplitudes as the dimensionless valve impedance ($Z_V^*$) varies for a frictionless pipe simulation ..........................................................................47

Figure 3.5 Variation of the leak-induced pattern amplitudes according to changes in the dimensionless leak impedance ($Z_L^*$) for a frictionless pipe simulation ..................................................................48

Figure 3.6 A dimensionless FRD for the pipeline system in the case study, $x_L^* = 0.1$ ..........................................................................50

Figure 3.7 A dimensionless FRD for the pipeline system in the case study, $x_L^* = 0.9$ ..........................................................................51

Figure 3.8 Variation of the dimensionless leak-induced pattern amplitudes according to changes in the dimensionless valve impedance ($Z_V^*$), for case study with steady friction.................................................52

Figure 3.9 Variation of the dimensionless leak size ($C_{Ld}A_L / A$) (derived from the odd and the even harmonics, respectively) for changes in the dimensionless steady-state valve impedance ($Z_V^*$), for the case study with steady friction ............................................................ 53

Figure 4.1 A reservoir-pipeline-valve system with a leak. ............................ 76

Figure 4.2 Impact of the dimensionless leak location $x_L^*$ on the dimensionless peak values of the first three resonant responses, with $Z_V / Z_L = 1$ 87

Figure 4.3 Impact of the dimensionless leak location $x_L^*$ on the three coefficients $C_1$, $C_3$ and $C_5$ in Eq. (4.14), with $Z_V / Z_L = 1$ .......... 88

Figure 4.4 Impact of the dimensionless leak location $x_L^*$ on the two coefficients $C_1'$ and $C_3'$ in Eq. (4.19) ........................................... 93

Figure 4.5 Numerical FRDs for the case study $x_L^* = 0.2$ ............................... 97

Figure 4.6 The relative deviation between the estimated leak location and the actual leak location (solid lines), and the relative deviation between the estimated leak size and the actual leak size (dashed lines) ...... 99

Figure 5.1 An *n*-Stage shift register with XOR feedback for MLBS generation ............................................................................................... 124

Figure 5.2 Percentage error at the first resonance (frequency response at 2.5 Hz) as a function of the magnitude of valve perturbation ........... 126

Figure 5.3 Comparison between the FRD from MOC using the MLBS and the IRS excitation with $\Delta\tau / \tau_0 = 0.4$ and the linear FRD from the transfer matrix method ............................................................... 127

Figure 6.1 The customized transient generator used for generating MLBS and IRS ............................................................................................ 141

Figure 6.2 A schematic diagram of the experimental pipeline used in this research........142

Figure 6.3 The normalized IRS $\tau$ perturbation (input) in the case study No.1........144

Figure 6.4 The head perturbation (output) in the case study No.1........145

Figure 6.5 Comparison between the experimental FRF induced by IRS and MLBS excitation with the theoretical FRF in case study No.1....146

Figure 6.6 The normalized IRS $\tau$ perturbation (input) in the case study No.2........147

Figure 6.7 The head perturbation (output) in the case study No.2........148

Figure 6.8 Comparison between the experimental FRF induced by IRS and MLBS excitation with the theoretical FRF in case study No.2....149

Figure 6.9 The normalized IRS $\tau$ perturbation (input) in the case study No.3........151

Figure 6.10 The head perturbation (output) in the case study No.3........151

Figure 6.11 Comparison between the experimental FRF induced by IRS and MLBS excitation with the theoretical FRF in case study No.3....152

Figure 7.1 A Reservoir-Pipe-Reservoir system (which is equivalent to a RPV-Open Valve system) and the corresponding arrangement of the pressure transducer and a side-discharge valve transient generator for the extraction of the FRD........167

Figure 7.2 A Reservoir-Pipeline-(in-line) Valve (RPV) system and the corresponding arrangement of the pressure transducer and a side-discharge valve transient generator for the extraction of the FRD. When the in-line valve is fully closed, it forms a RPV-Closed Valve configuration; when the in-line valve is slightly open, it forms a RPV-High Loss Valve configuration........170

Figure 7.3 Dimensionless frequency response diagrams (FRDs) of a RPV system with a leak ( $Z_L^* = 10$ , $x_L^* = 0.3$ ). The shape of the FRD changes with the value of the dimensionless valve impedance $Z_V^*$ ........................................................................................ 175

Figure 7.4 The system layout of the experimental pipeline......................... 177

Figure 7.5 Normalized frequency response diagrams (including the first three resonant peaks) for the experimental pipeline. The peak at A is the result of low signal-to-noise ratio at the frequency of 0.5 $f_c$ (i.e. 50 Hz in this experiment), where the theoretical power of the IRS is zero........................................................................................ 179

Figure 8.1 Wave propagating through a deteriorated section (designated with length $L_1$ , impedance $B_1$ , and wave speed $a_1$ ): (a) a step incident wave is approaching the deterioration from the right side; (b) the first reflection and transmission occur at the right boundary of the deterioration; (c) the second reflection and transmission occur at the left boundary of the deterioration; (d) the third reflection and transmission occur at the right boundary of the deterioration. .... 196

Figure 8.2 Distributed deterioration detection at an interior location within the pipeline: (a) the steady state condition; (b) the incident wave generated by the closure of the side-discharge valve.................. 201

Figure 8.3 The experimental pipeline system layout.................................. 205

Figure 8.4 Experimental pressure trace of Test 1 ....................................... 205

Figure 8.5 The first plateau of experimental head response traces. Three experiments (Tests 1 to 3) on a pipeline with a section of thinner wall thickness, compared to one experiment on an intact pipeline ........................................................................................ 206

Figure 8.6 Enlarged view of the wave front in Test 1 ................................. 207

Figure 8.7 Enlarged view of the pressure perturbation in the first plateau of the pressure trace measured in Test 1 .......................................... 207

Figure 8.8 Pressure response traces obtained from numerical simulations: Case 1: Using the experimental pipeline configuration and a vertical wave front; Case 2: Using the experimental pipeline configuration and the measured wave front; Case 3: Using the measured wave front, and the modified pipeline configuration, in which the length of the deterioration is doubled; Test 1: The experimental pressure trace from Test 1 ..................................... 214

Figure 8.9 Deterioration-induced pressure perturbations obtained from numerical simulations (enlargement of Figure 8.8): Case 1: Using the experimental pipeline configuration and a vertical wave front; Case 2: Using the experimental pipeline configuration and the measured wave front; Case 3: Using the measured wave front, and the modified pipeline configuration, in which the length of the deterioration is doubled; Test 1: The experimental pressure trace from Test 1 ..................................................................... 214

Figure 9.1 Variation of the normalized head perturbations for the reflected wave ($H_r^*$, solid line) and transmitted wave ($H_t^*$, dashed line) according to variations in the impedance ratio ($B_r$) ................... 231

Figure 9.2 Variation of the normalized head perturbation of the reflected wave ($H_r^*$) according to a relative change in wall thickness ($e_{rc}$) from the internal side of a pipeline .......................................................... 236

Figure 9.3 Variation of the normalized head perturbation of the transmitted wave ($H_t^*$) according to a relative change in wall thickness ($e_{rc}$) from the internal side of a pipeline............................................. 237

Figure 9.4 Variation of the normalized head perturbation of the reflected wave ($H_r^*$) according to a relative change in wall thickness ($e_{rc}$) from the external side of a pipeline.......................................................... 240

Figure 10.1 (a) An example pipeline system; and (b) its MOC grid for conventional MOC analysis. 255

Figure 10.2 (a) An example pipeline system; and (b) a possible MOC grid reconstructed by the reconstructive MOC analysis (note that the pipeline properties can be different between reaches). 258

Figure 10.3 An example pressure trace resulting from a rapid valve closure and measured at the upstream face of the closed valve 261

Figure 10.4 MOC analysis at point $x_0$ for determining $B_1$ 261

Figure 10.5 Reconstructive MOC analysis for the second pipe section 263

Figure 10.6 MOC analysis for point $x_1$ at $t = \Delta t / 2$ 264

Figure 10.7 Pipeline configuration for the numerical simulation. 267

Figure 10.8 Pressure trace obtained in the forward MOC modeling (the first plateau, i.e. from the initial wave jump to the first reflection from the reservoir). 268

Figure 10.9 Impedance ($B$, on the left axis) and wave speed ($a$, on the right axis) estimated from the reconstructive MOC analysis for the numerical simulations 269

Figure 10.10 System layout of the experimental pipeline. 271

Figure 10.11 First plateau of the experimental pressure trace 272

Figure 10.12 Plot of the unit step response function (SRF) estimated from the measured pressure trace (SRF for $Q_0$ = 1 m$^3$/s) 274

Figure 10.13 Impedance ($B$, on the left axis) and wave speed ($a$, on the right axis) estimated from the reconstructive MOC analysis for the experimental pipeline 274

Figure 11.1 Pipeline configuration for transient wave measurement with illustration of wave propagation; $R_u$ and $R_d$ represent the reflected waves traveling upstream and downstream respectively with respect to where transducer $T_{p1}$ is located ..................................291

Figure 11.2 Theoretical behavior of a steep pressure wave crossing a discontinuity of impedance ( $H_0$ = steady-state head; $H_i$ = head of the incident wave; $H_{j1}$ = head of the reflected and transmitted waves; $B_1 < B_0$ ) ..........................................................................298

Figure 11.3 Discretization of a section of pipe using a MOC grid for the reconstructive transient analysis. Note that the properties of each pipe reach ( $\Delta x_i, a_i, B_i$ ) are unknown and yet to be determined. The pair of transducers are $T_{p1}$ and $T_{p2}$ .............................................300

Figure 11.4 Evolution of the transient wave propagation within the first time step. Arrows represent the direction of the wave propagation .....302

Figure 11.5 Pipeline configuration for the numerical simulations................306

Figure 11.6 Pressure traces measured by the pair of transducers in the numerical simulation. $H_1(t)$ is from transducer $T_{p1}$ and $H_2(t)$ is from transducer $T_{p2}$ .....................................................................307

Figure 11.7 The pressure trace of the reflected wave $R_u(t)$ that travels upstream ..........................................................................................308

Figure 11.8 The pressure trace of the reflected wave $R_d(t)$ that travels downstream ......................................................................................308

Figure 11.9 The input and the output signals for determining the unit step response function (SRF) of the pipe section upstream from the transducers..........................................................................................309

Figure 11.10 Comparison between the estimated unit step response function (SRF) with the theoretical unit SRF determined from MOC modeling ........................................................................ 310

Figure 11.11 The distribution of impedance and wave speed estimated from the reconstructive transient analysis ........................................... 311