Role and characterization of leaks under transient conditions

Kai Wah Tang (1), Bruno Brunone (2), Bryan Karney (3), and Andrea Rossetti (4)

(1) Graduate Student, Department of Civil Engineering, University of Toronto, Toronto, M5S 1A4, Ontario Canada; email: kwtang@civ.utoronto.ca
(2) Assoc. Prof. of Hydr., Department of Water and Struct. Engineering, University of Perugia, via G. Duranti 93, 06125 Perugia, Italy; email: brunone@unipg.it
(3) Professor, Department of Civil Engineering, University of Toronto, Toronto, M5S 1A4, Ontario Canada; PH (416) 978-7776; FAX (416) 978-7776; email: karney@civ.utoronto.ca
(4) Research Assistant, Department of Water and Struct. Engineering, University of Perugia, via G. Duranti 93, 06125 Perugia, Italy

Abstract

The significance and impact of leaks in a pipeline system creates new opportunities of leak detection. In essence, the concept is to use the pressure response from a transient event to locate and size a leak. Previously, Brunone (1999), determined both the location and size of a leak on the basis of the pressure trace during a transient event at a measurement section on the basis of the well-known properties of pressure waves. More recently, formal inverse transient algorithms have been developed. The goal in this study is to see if the genetic inverse transient procedure can correctly locate and size a leak in a "blind test". More specifically, the pressure signal at the downstream end of the system as well as the basic pipe properties will be fed to the inverse procedure to see if the predicted existence, location and magnitude of the leak can be accurately determined. The paper reviews the results of the blind calibration procedure as well as summarizing the key background required to understand these developments. The significance of this study data to the later quality problem, and particularly to the danger of contamination of the pipe contents, are given special emphasis.

Introduction

Leaks are a serious and challenging concern to operators of water distribution systems. Not only do they allow treated water to escape uselessly into the environment, they dissipate a considerable amount of energy as well, thereby increasing both pumping costs and the environmental footprint of a water supply project. Despite these serious concerns, other aspects have more recently been receiving attention. For example, Funk et al. (1999) point out that leaks create a two-way connection between the inside of a pipe and its immediate environment, thus introducing the possibility of drawing contaminated water into a pipeline under suitable (e.g., transient) conditions.

This particular leak detection experiment utilizes a genetic algorithm (GA) inverse calibration computer program for pipe networks developed in the last 2 years. This software is actually a combination of a genetic algorithm processor (GAP) and a transient pipe network analysis program (TransAM) created to perform inverse calibration using field data collected from transient events. This combination of computer algorithm and software lends itself readily to the task at hand. Since the program can calibrate for any number and type of parameter in a pipe network system, it can be used to calibrate for leak(s) in the test system.

The genetic inverse calibration approach borrows from nature, using its intelligence and wisdom in the simple form of genetics. Nature has been "calibrating" species and individuals to survive in the ecosystem for billions of years. The simple rule followed in nature is to create a large gene pool, to allow the organisms or individuals to interact with each other and the environment to determine who are the most appropriate individuals to pass on their genes to the next generation. Through reproduction and occasional mutation, this process generally produces individuals that are better suited to survive in their environment: hence the expression, "survival of the fittest."

In this study, we would like to calibrate models of pipe network systems. In some senses, a pipe network is not unlike a living organism. It has physical characteristics, specific needs and behaves with a certain degree of certainty. Therefore, one can model the physical characteristics of the system such as pipe diameters, friction values, wavespeed, valve sizes (leaks), pumps and other devices as specific genes in an individual "artificial" organism.

In the current application, the individuals of a species are not used, but the analogy to genetics is still strong. In fact, the leak test system is viewed as an environment inhabited by "individuals" (data files) that have physical characteristics such as pipe friction factors, wave speeds, valve operating scenarios and leaks represented as valves discharging to the atmosphere. Each artificial individual contains all parameters being calibrated as genes.

Genetic Algorithm

In order to carry out the calibration of the leak test system, we can populate our pipe network "biosphere" with many organisms (large gene pool) with a large diversity of genes representing the physical characteristics of the system.

The genetic algorithm as applied to a pipe network involves 3 major steps. In step 1, gene typing, all relevant physical values calibrated for are encoded into binary numbers. The binary number system is a logical choice for gene encoding since a binary number consists of a number of bits that is either a 1 or 0. A binary 1 can represent that a particular gene is switched on and a binary 0 is a switched off gene. Therefore an individual contains a number of genes, each a binary number representing a physical characteristic value. Since each characteristic can take on a number of values, the algorithm requires a lower and an upper bound for each parameter. For example, a 7 bit binary number with a possible numerical range of 0 to 127 can be used to represent the friction value of a particular pipe in the system. The following binary number (0010010) is equivalent to a Hazen Williams friction factor of 111.3 if the upper and lower bounds are 180 and 100 respectively. If each parameter is represented by 7 bits, they can take on 128 different values.

In step 2, Inverse Calibration, the individual s genes are converted to their actual physical parameter values. Since each individual as in nature, contains all the physical characteristics of the system, they can be used as data for a transient analysis computer model. The current process differs from traditional techniques in that the calibration is performed on a non-steady state, or "actual" condition, network. This feature allows for simple on-line collection of thousands of pieces of information, using three or four high speed pressure transducers. These data can then be used to effectively solve or calibrate the model.

The reason that a transient model is used instead of a steady state model is that a transient is very specific and short lived, and only one particular set of parameters and/or events is likely to reproduce it in detail. Whereas, a number of different paths or ways can be found to reach steady state which are not necessarily always physically evolved. Since a transient wave is specific to the actual system, measurements of the system in terms of pressure heads during a transient event can be used as a check on how well each individual (data file) can mimic through a computer simulation, the actual transient. Therefore, in order to carry out an inverse calibration of the system, we need very accurate and fast head measurements at one or a number of locations in the system to capture the transient event.

And in the final stage, before the cycle repeats itself, the individuals of a population are ranked in order of their ability to accurately predict the response of the system to a particular transient event. The evaluation scheme is quite simple, we check to see how well the individual modeled the real system. In order to perform this check, information about the real system must be obtained. For pipe networks, pressure measurement makes a logical choice as information that characterizes the system behaviour. Armed with this information, we can numerically model the system with each individual in the population and compare the computer generated pressures with the measured values and calculate an error function. It is this error value that determines the superiority of the individual (minimum error represents best individual). Once the "best" individual is determined for any particular generation, the next generation is evolved. We allow the "better" individuals to reproduce and generate new "additions" to the gene pool. The reproduction process involves taking genes from two parents and combining them through genetic cross-over. As in nature, mutation is allowed to further enhance the gene pool. The "best" individual from the previous generation is allowed to join the new generation through elitism. This ensures that all new generations will perform better or equal to the past generations. The new generation is produced and the members are once again evaluated and ranked in order of superiority. After a sufficient number of generations, we should find that the best individuals have similar if not identical characteristics as the actual system.

Leak Test System

The first step in the leak detection procedure involved setting up a TransAM model of the test system. The blind tests were carried out at the Hydraulics Laboratory of the University of Perugia (Italy) in a polyethylene pipe, 352 m long, with internal diameter of 93.8 mm and wall thickness of 8.1 mm. The pipe is arranged in concentric circles (Figure 1) with bends having a minimum radius equal to 1.5 m and is almost horizontal, except for the last short part. For the supply reservoir, an air vessel is used in which the pressure is kept automatically constant and equal to a prescribed value by varying the speed of three submerged pumps placed in the recycling reservoir. At the end section of the pipe, a hand operated ball valve is present discharging in air.

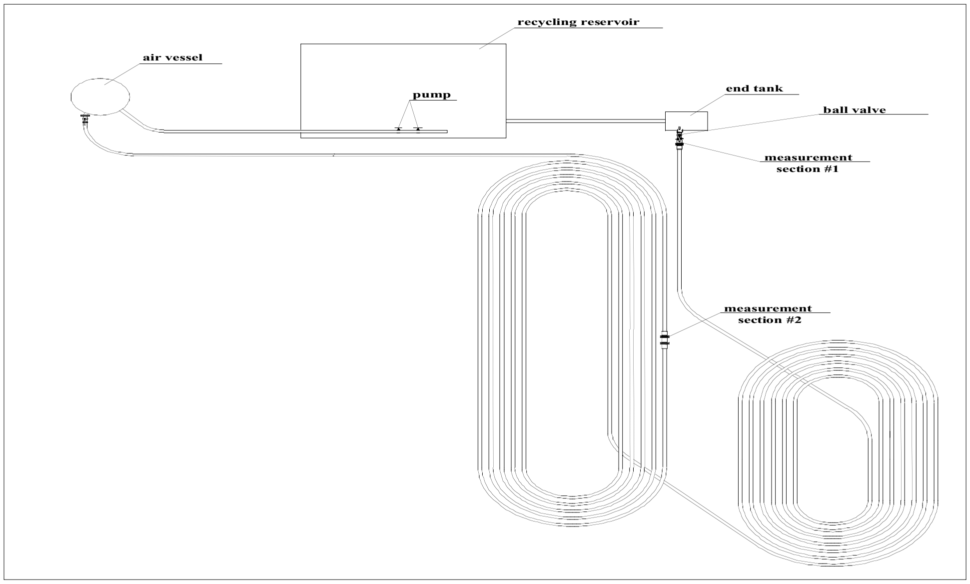

Figure 1. The laboratory test apparatus for simulating leak(s).

The leak simulations were carried out under the following conditions:

1) simulation of the leak in the laboratory test

In order to simulate the leak, a device with an orifice at its wall has been used (Figure 2); the leak discharges in air. The performance of two types of leaks were investigated (this information was not known a priori to the genetic inverse transient leak detection investigation); specifically, a circular orifice with different sizes (*d* equal to 7.5 mm for test no. 2, 3, and 4 and *d* equal to 12.5 mm for test no. 14 and 16, respectively, with *d* being the orifice diameter).

2) the characteristics of the unsteady-state tests

The experiments entailed observation of the pressure signal in a damaged pipe during transients generated by the complete closure of the ball valve. In all tests, valve motion was fast, with the duration T smaller than $2s_l/a$, where $2s_l$ was the distance of the leak from the downstream end valve and a was the wavespeed. Since small values of the steady-state flow rate at the end section of the pipe were fixed as initial conditions, the reliability of the proposed technique has been tested within a pressure regime suitable to operative pipe systems, i.e., small overpressures during transients.

3) the measurements

Pressure measurements were made at the supply reservoir, as well as at the section just upstream of the valve (the *measurement section*). Pressure transducers are of the strain-gauge type, with a recording range of 0 to 60 m of water column, an accuracy of 0.5% of the full-range scale and a time response of 50 ms. Output signals from pressure transducers are read directly into a PC at a rate of 50 - 150 Hz. The steady-state flow rate upstream of leak, Qu, was measured by means of discharge magnetic meters.

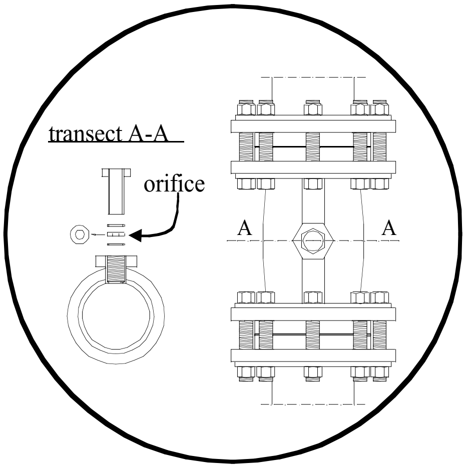

Figure 2. Device simulating the leak.

The data supplied for this experiment was limited to pressure measurements at the upstream end and at the downstream valve. The discharge upstream of the leak is also recorded. The five leak samples numbered 2, 3, 4, 14 and 16 are measured at a sampling rate of 100 Hz. Table 1 typifies the sample data collected from blind tests #3 and #4:

Table 1. Typical data collected from simulated leak tests

	Test 3				**Test 4**		
Time (s)	**hr (m)**	**Qu (l/s)**	**Hvalve (m)**		**hr (m)**	**Qu (l/s)**	**Hvalve (m)**
0.00	11.52	2.72	10.86		11.65	3.51	10.56
0.01	11.52	2.72	10.86		11.65	3.51	10.64
0.02	11.52	2.70	10.86		11.77	3.49	10.64

hr - head at upstream reservoir
Qu-Flow rate upstream of leak
Hvalve-head at downstream control valve

Numerical Model

The TransAM model (e.g., Karney & McInnis, 1992) developed for the test system consists of 15 nodes and 14 pipes (25 m lengths). The upstream end of the system is modeled as a constant head reservoir with a water level consistent with each of the five test runs. The downstream end of the system is represented by a valve discharging to the atmosphere. The leak is also configured as a valve discharging to the atmosphere. Since the size and location of the leak is unknown (blind test), the size and node at which the leak valve is located are parameters to be determined by the genetic inverse transient calibration procedure.

The second step in the process focuses on the measured data. The data provided was collected at a sampling rate of 100 Hz for the duration of approximately 30 seconds, therefore a lot of data was available for analysis. However, not all of the data was necessary to carry out the investigation. It was recognized that most one-dimensional transient analysis models like TransAM will only be able to reproduce accurately the first or second transient pressure waves. Thus, only the significant portions (first two waves) of the measured data were isolated for calibration purposes as illustrated in Figure 3.

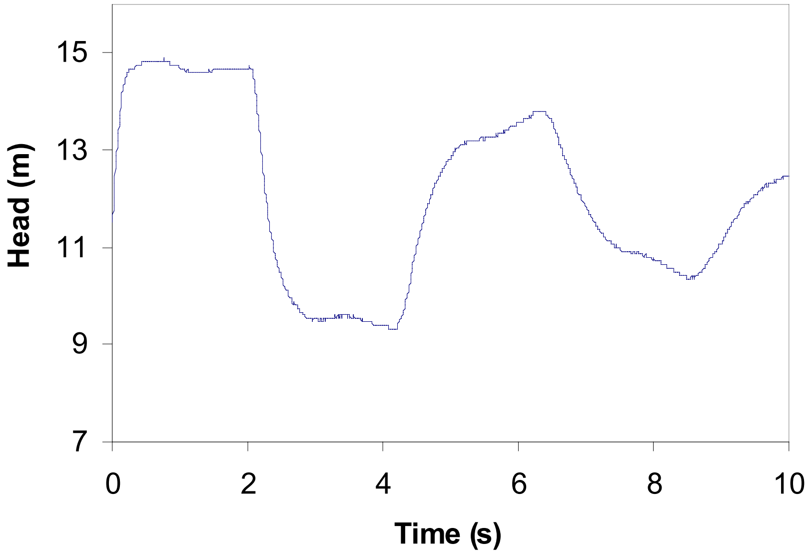

Figure 3. Pressure measurements at downstream valve for test#2.

Inverse Transient Analysis

Once the measured data are prepared, investigative TransAM data files were created and tested against the measured data to determine the approximate steady state conditions at the start of each test run. Since no physical information about the control valve or its operation was available, it was necessary to include its characteristics in the inverse calibration. These trial runs provided constraining values for the size of the downstream valve and the size of the leak. The result is a set of range values for the valve sizes for each test run. These ranges are used in the genetic calibration processor to define the search space.

The initial tests conducted utilized the transient signature of the first two transient pressure waves as illustrated in Figure 4. The leak was setup as a valve to atmosphere that was allowed to occupy a node in the nodal range from 2 to 14 (i.e., any node between the upstream and downstream end of the pipeline). Independent genetic inverse calibrations were performed with a population size of 500 and 4 generations for each simulated leak test. The time required for each run was 3.5 hours on a Pentium 450c computer. The results from these investigations were tabulated into Table 2.

Table 2. Results from initial calibrations

Leak	Test #2	Test #3	Test #4	Test #14	Test #16
Node	12	8	8	12	12
Location	75 m	175 m	175 m	75 m	75 m

Note: Leak location is distance in meters from the downstream valve.

Although the initial results were not conclusive, they did provide insight into refining the inverse leak detection procedure. The results indicated that the leak could be located between nodes 8 and node 12. Therefore, the next set of calibrations focused on locating the leak in nodes 8 through 12. It was also evident from the calibrations that only 3 generations will be required to produce good results. The next set of calibration runs was carried out with a population size of 700 and 3 generations. The limiting of the search for the leak to nodes 8 through 12 did not produce any new information or a consensus on the leak node/location. A possible reason for this was mentioned earlier in the discussion on one dimensional transient analysis models such as TransAM. That is TransAM like many of its kind can not predict accurately the friction losses due to velocity profile changes. This usually results in a more conservative modeling of friction losses during a transient event. One dimensional transient analysis programs can accurately predict the first transient wave, however the subsequent waves are not modeled as effectively. Figure 4 shows one of the results from this stage of the investigation. It illustrates that the one dimensional transient model does have difficulty with predicting the shape of the second pressure wave.

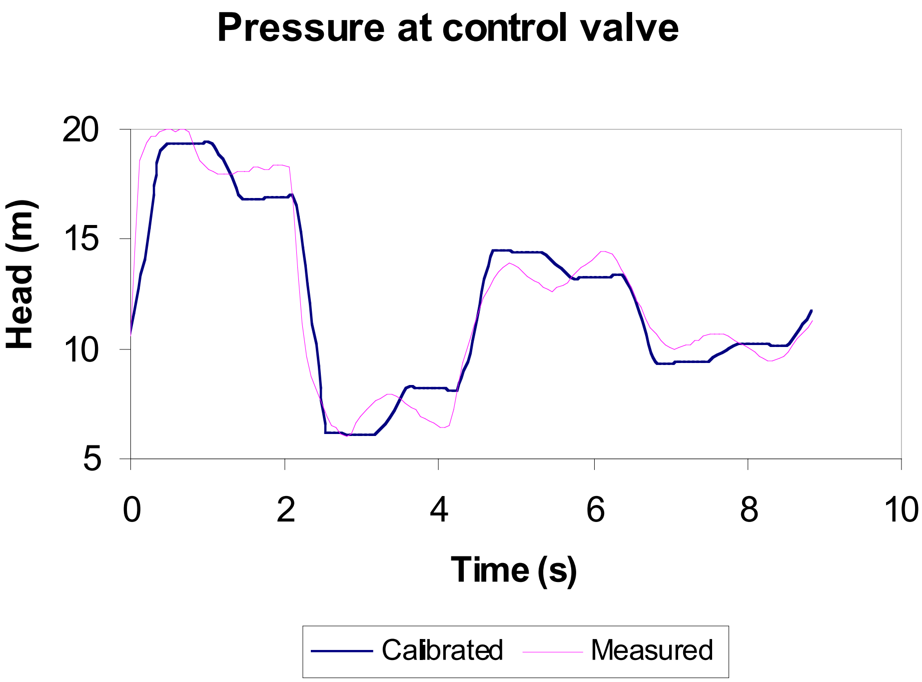

Figure 4. Initial calibrated results for test#16.

Therefore, the next set of independent calibration runs will utilize only the data for the first pressure wave measured from each test sampled. The search for the leak will continue to focus on nodes 8 through 12. Table 3 summarizes the results of this search.

Table 3. Final calibration results

Leak	**Test #2**	**Test #3**	**Test #4**	**Test #14**	**Test #16**
Node	12	10	10	10	10
Location	75 m	125 m	125 m	125 m	125 m
Size	0.5 l/s	0.61 l/s	0.68 l/s	1.30 l/s	1.34 l/s

Note: Leak location is distance in meters from the downstream valve.
Leak size is the steady state discharge from the leak indicating its size.

Although test#2's result does not agree with the other tests, there appears to be a consensus on the location of the leak. The leak is independently found by test#3, test#4, test#14 and test#16 to be located at node 10 or 125 m from the downstream control valve. When the "blind fold" is taken off, the actual location of the leak was 128.5 meters from the downstream valve. Since the computer model of the test system was configured with 25 m lengths of pipes, we had expected to be a few meters off target. If the exact location of the leak is required, the computer model can be revised with shorter lengths of pipe. However, this is not critical since a difference of a few meters is not significant. Figure 5 illustrates the close approximation of this inverse leak detection procedure.

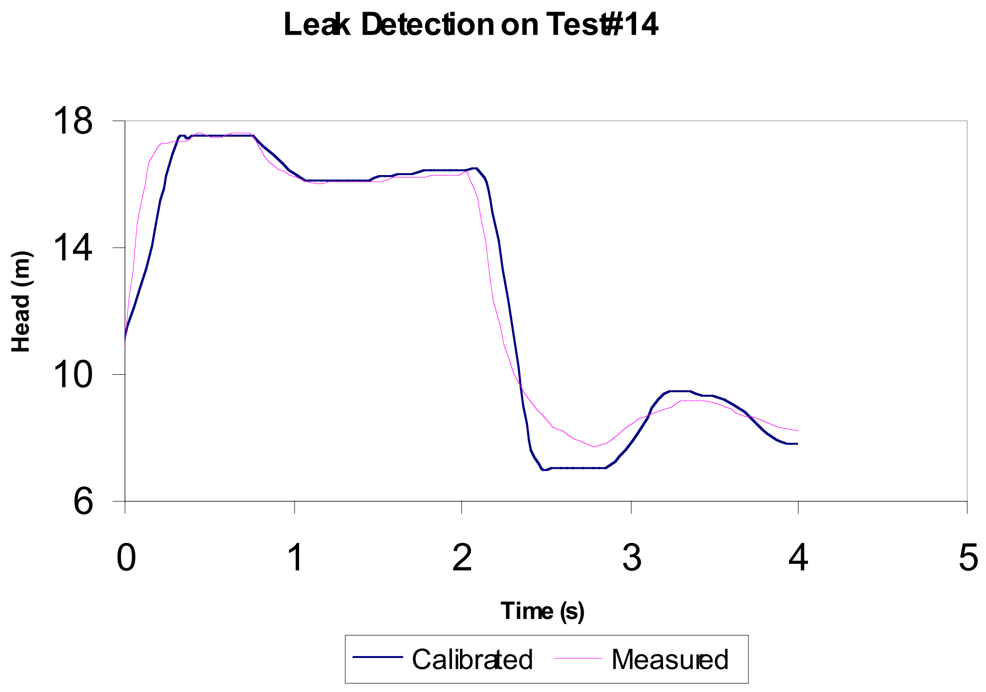

Figure 5. Final leak detection/calibration pressure head at control valve.

After analyzing test#2's calibration data, it was determined that the inverse procedure could not differentiate between locating the leak at nodes 9, 10, 11, or 12. This may be the result of test#2's low initial flow rate (1.25 l/s) which in turn generates much smaller transient pressure waves. The various uncertainties in the estimation of pipe friction values, pipe wavespeeeds, changes in flow around the leak site, and operational characteristics of the control valve can induce transients that may be more influential than the transients caused by not placing the leak at its actual location.

Conclusion

In conclusion, the genetic inverse transient calibration procedure tested in this paper can predict accurately the size and location of a leak in a pipeline. The independent calibrations carried out during this investigation located the leak consistently. The genetic inverse transient calibration/leak detection also reliably estimated the size of the leak: as a matter of fact, orifice diameter for test no. 14 and 16 is larger than the one used in the other tests and discharge values reported in Table 3 confirm this.

The entire analysis required approximately two days of computing on an entry level personal computer with minimal user monitoring or input. Brunone(1999) has already demonstrated that measuring the travel time of the well-known properties of the transient pressure wave, one can detect the location of the leak very quickly, whereas by means of GAP one needs some hours. However, the potential of the GAP to handle more complex pipe systems is significant. In such a case, due to a possible large number of partial reflections of the pressure waves, it would be more difficult to locate the leak by means of the well-known properties of pressure waves.

However, the accuracy of predicting the exact location of the leak with the inverse method proposed here or most other methods can be hampered by very low flow velocities or small transient events. Even in such cases the genetic inverse transient method determined the leak location within the vicinity of the actual site of the leak as demonstrated by test#2's results. Therefore, genetic inverse transient calibration can be a cost effective means of locating leaks in simple and complex pipe systems. In the future, the inverse leak detection method developed in this paper may be improved by exploring a variety of GA strategies.

References

Brunone, B. (1999), Transient Test-Based Technique for Leak Detection in Outfall Pipes. *J. of Water Resources Planning and Management*, 125(5), 302--306.

Chaudhry, M.H. (1987). *Applied Hydraulic Transients*. Van Nostrand Reinhold, New York, N.Y.

Clingenpeel, W.H. (1983). Optimizing pump operating costs.: Management and Operations, *J. AWWA*, 502--509.

Dandy, G. C., Simpson, A. R. and Murphy L. J. (1996). An improved genetic algorithm for pipe network optimization. *Water Resources Research*, 32(2), 449-458.

Goldberg, D. E. and Kuo, C. H. (1987). Genetic algorithms in pipeline optimization. *J. Computing in Civ. Engrg.*, ASCE, 1(2), 128-141.

Halhal, D., Walters, G. A. and Savic, D. A. (1997). Water network rehabilitation with structured messy genetic algorithm. *J. of Water Resources Planning and Management*, 123(3), 137-146.

Holland, J. H. (1975). *Adaptation in Natural and Artificial Systems*. University of Michigan Press, Ann Arbor, Mich.

Hadji, G. and Murphy, L. J. (1990). Genetic algorithms for pipe network optimization. 4th Year Student Civil Engineering Research Report, University of Adelaide, Australia. pp. 134.

Karney, B.W., and McInnis, D. (1992). Efficient calculation of transient flow in simple pipe networks. *Journal of Hydraulic Engineering*, ASCE, Volume 118, No. 7, 1014--1030.

Liggett, J.A. and Chen, L-C. (1994a). Inverse transient Analysis in Pipe networks. *J. Hydr. Engrg.*, ASCE, 120(8), 934--955.

Liggett, J.A. and Chen, L-C. (1994b). Monitoring water distribution systems: the inverse method as a tool for calibration and leak detection. In: *Improving efficiency and reliability in water distribution systems*, E. Cabrera and Antonio F. Vela, editors, Valencia, Spain, Kluwer Academic Publishers, 107--134.

McInnis D., Karney, B. and Axworthy, D. (1997). TRANSAM Reference Manual. HydraTek Associates, (Ajax).

Murphy, L. J. and Simpson, A. R. (1992). Pipe optimization using genetic algorithms. Research Report No. 93, Department of Civil Engineering, University of Adelaide, Australia, June, pp. 95.

Murphy, L. J., Simpson, A. R. and Dandy, G. C. (1993). Design of a pipe network using genetic algorithms. Water, pp. 95.

Savic, D. A. and Walters, G. A. (1997). "Genetic algorithms for least-cost design of water distribution networks." J. of Water Resources Planning and Management, 123(2), 67-77.

Simpson A. R., G. C. Dandy and L. J.Murphy (1994). Genetic algorithms compared to other techniques for pipe optimization. *Journal of Water Resources Planning and Management*, Vol. 120, No. 4, July/August.

Simpson, A. R., Murphy, L. J. and Dandy, G. C. (1993). Pipe network optimization using genetic algorithms. Proc., ASCE, *Water Resources Planning and Management* Special Conf., Seattle, Washington, May, 392-395.

Walters, G. A. and T. Lohbeck (1993). Optimal layout of tree networks using genetic algorithms. *Engrg. Optim.*, 22, 47-48.

Wylie, E.B., and Streeter, V.L. (1993). Fluid transients in systems. Prentice-Hall, Inc., Englewood Cliffs, N.J.