Using Electrical Resistance Networks to Enhance Performance Assessment of Water Distribution Networks

G. Moser[1], S. German Paal[1], D. Jelaty[2], I. F. C. Smith[1].
(1) Swiss Federal Institute of Technology (EPFL) – Switzerland
(2) Georgia Tech., Atlanta, USA

Abstract

Pressurized fluid-distribution networks are strategic elements of civil infrastructure. In the case of fresh-water distribution networks, where leaks are common and where real performance is unknown, advanced sensor-based diagnostic methodologies have the potential to provide enhanced management support. A structural identification methodology that has been used successfully for bridges is adapted to a study of a diagnostic methodology for leak detection in water distribution networks. This methodology is based on error-domain model falsification. Using analogies between Ohm's law and the Hazen-Williams relationship, an electric network model is built to show similarities with hydraulic networks. The first step is to compare simulated values to show similarity of the network behaviour and then to show similarities throughout the diagnostic process. This study establishes the similarity of the behaviour for hydraulic and electrical networks. It also shows that results obtained with electrical networks are relevant for performance assessments of hydraulic networks. These results present to practicality of studying generic electrical networks of varying size and shape to illustrate the usefulness of the diagnostic methodology for general cases.

1. Introduction

Fresh water is a key resource when considering sustainable development. Drinking water needs to be preserved, and this includes waste prevention. This can be achieved by reducing water lost through leaks, by using an efficient monitoring system for leak detection.

Leak detection monitoring techniques are principally based on noise, pressure and flow measurement (Xu et al., 2014). Techniques based on measuring variations in the hydraulic state (pressure and flow) due to the presence of a leak can be separated into two groups. The first is transient-based; these techniques use measured transient signals (usually the pressure) to detect leaks (Vítkovský et al., 2000, 2007, Whittle et al., 2010, Whittle et al., 2013, Srirangarajan et al., 2010). The second group is based on the study of steady-state regimes. These techniques are mainly based on comparisons of measurement with predictions obtained by simulating hydraulic numeric models. The goal is usually to find predictions which correspond to measurements. This can be done by optimization tasks (Pudar and Liggett, 1992, Andersen and Powell, 2000) and by Bayesian inference (Poulakis et al., 2003, Rougier, 2005, Puust et al., 2006, Barandouzi et al., 2012). It has been shown by Goulet and Smith (2013b) that these techniques lead to biased predictions in the presence of systematic uncertainties and subsequent unknown correlations.

To overcome this challenge, model falsification (Popper, 2002) can be used to interpret measurement data. This principle was first applied to leaks by Robert-Nicoud et al. (2005). Model falsification was developed further by Goulet and Smith (2013a); they developed a methodology called error-domain model falsification for infrastructure diagnosis. This methodology was applied to leak detection in a preliminary study by Goulet et al. (2013) and then by Moser and Smith (2013).

A challenge associated with developing leak-detection methodologies is that water-distribution networks are difficult to access as they are generally underground. Therefore, monitoring such systems is usually expensive, and once the sensors are installed, moving them to test other sensor configurations is often not feasible. For these reasons, development of a laboratory network is an attractive strategy. However, building hydraulic laboratory networks is costly and working with a network that is complex enough to represent a real network would be arduous.

This paper describes a proposal for electrical resistance networks that have behaviors which are similar to water distribution networks and are less complex to build. Parallels between electric and hydraulic networks are often used in order to better understand concepts of electric networks (Greenslade Jr., 2003). Assimilating electric current with the flow of a fluid and voltage with the pressure is an easy way to illustrate basic electrical behavior.

Such parallels have already been used by several researchers. Techniques to reduce water distribution networks into a simpler equivalent network have been developed (Ulanicki et al., 1996, Martinez Alzamora et al., 2014). Oh et al. (2012) reviewed the application of electric circuits for the analysis of pressure-driven microfluidic networks. Aumeerally and Sitte (2006) used electric networks to model the flow-rate of micro-channels.

Electrical analogies have also been used in fields other than hydraulics. Various systems have been modeled by electric networks such as DNA structures (Marshall, 2009, Marshall, 2010, Roy et al., 2014), stomata networks (Berg, 2014) and tidal stream power resources (Draper et al., 2014). However, no previous research has been found regarding the use of electric networks for testing monitoring strategies such as leak-detection methodologies in water-supply networks.

This paper compares the behavior of an electric network model with a hydraulic network model for leak detection using the error-domain model falsification data interpretation approach. First, direct similarities are shown by comparing results obtained from simulations of both models. These models are then used to demonstrate similarities through data interpretation.

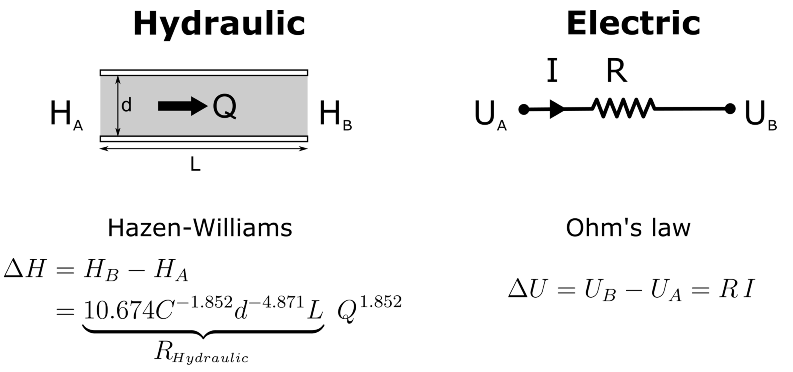
Section 2 describes the error-domain falsification methodology and the analogies between the electric and hydraulic networks used in this paper. Section 3 presents the results of the comparisons of electric and hydraulic networks. Finally, Section 3 includes a discussion of results and opportunities for further research.

2. Methodology

In this section, analogies between electric and hydraulic networks are explained. Also, the manner in which a model of an electric network is built based on the model of a hydraulic network using these analogies is described. Finally the principle of model-falsification used for leak detection is described.

2.1 Hydraulic/Electric analogies

Figure 1 illustrates similarities that can be established by comparing flow in a pressurized pipe with direct current (DC) going through a resistor. In the hydraulic case, the Hazen-Williams equation gives the head loss (ΔH) as a function of flow and the pipe characteristics (diameter d, length L and Hazen-Williams roughness coefficient C). In the electric case, Ohm's law states that the difference of potential (ΔU) is obtained by multiplying the current (I) with the resistance (R).
By regrouping all the terms in the Hazen-Williams equation that are physical parameters of the pipe into one term, the hydraulic resistance ($R_{Hydraulic}$), the resemblance between the Hazen-Williams equation and Ohm's law is shown. The difference is that Ohm's law is a linear relation while the Hazen-Williams equation represents a non-linear relationship (due to the power of the flow).



$$\Delta H = H_B - H_A = \underbrace{10.674 C^{-1.852} d^{-4.871} L}_{R_{Hydraulic}}\ Q^{1.852}$$

$$\Delta U = U_B - U_A = R\,I$$

Figure 1 Similarity between hydraulic pipe and electric resistor

For this study, a model of an electrical network is built based on a hydraulic model of a water distribution network. Pipes in the water network are replaced by resistors in the electrical network. The value of the electric resistance is chosen equal to the hydraulic resistance of the corresponding pipe. Because water distribution is governed by the demand at the nodes, each node of the electric model is connected to a current sink that removes the appropriate amount of current from the network.

To make the results comparable, values of current removed at current sinks are calculated to correspond to the values of the demand for the hydraulic network model. For example, if the demand at one node is one cubic meter per second then the current sink at the same node removes one Ampere from the electric network.

2.2 Model falsification

Model falsification is based on comparison of measurements with predictions obtained through simulating several scenarios. Each scenario represents a possible state of the system. The sampling objective is to have enough scenarios to cover all possible combinations of parameter values leading to a range of behavior of the system. The measurements are used to falsify the scenarios that are not compatible. The scenarios remaining, are called candidate scenarios, they represent the state of the system that could be described by the measurements.

For leak detection in water distribution networks, each scenario corresponds to a set of parameter values that represent characteristics of a leak (location and intensity) and characteristics of the network, such as the level in the tank and the flow entering at the pump. Because the main characteristic of the scenarios is the leak, they are called leak scenarios.

Figure 2 shows how the falsification process works. Measurements ($\boldsymbol{y}$) are compared with predictions ($\boldsymbol{g}(\boldsymbol{s})$) obtained by simulating each leak scenario with the model ($\boldsymbol{g}(\;)$). More precisely, for each scenario, the measurements are subtracted from the predictions. Then, if the difference obtained is not inside the interval defined by the thresholds ($[\mathbf{T}_{\mathbf{low}}, \mathbf{T}_{\mathbf{high}}]$), the leak scenario is falsified. These thresholds are obtained by combining the measurements ($\boldsymbol{u}_{\boldsymbol{meas}}$) and modelling uncertainties ($\boldsymbol{u}_{\boldsymbol{model}}$). The leak scenarios that remain after the procedure, the candidate leak scenarios, are the leaks that could be described by the measurements.

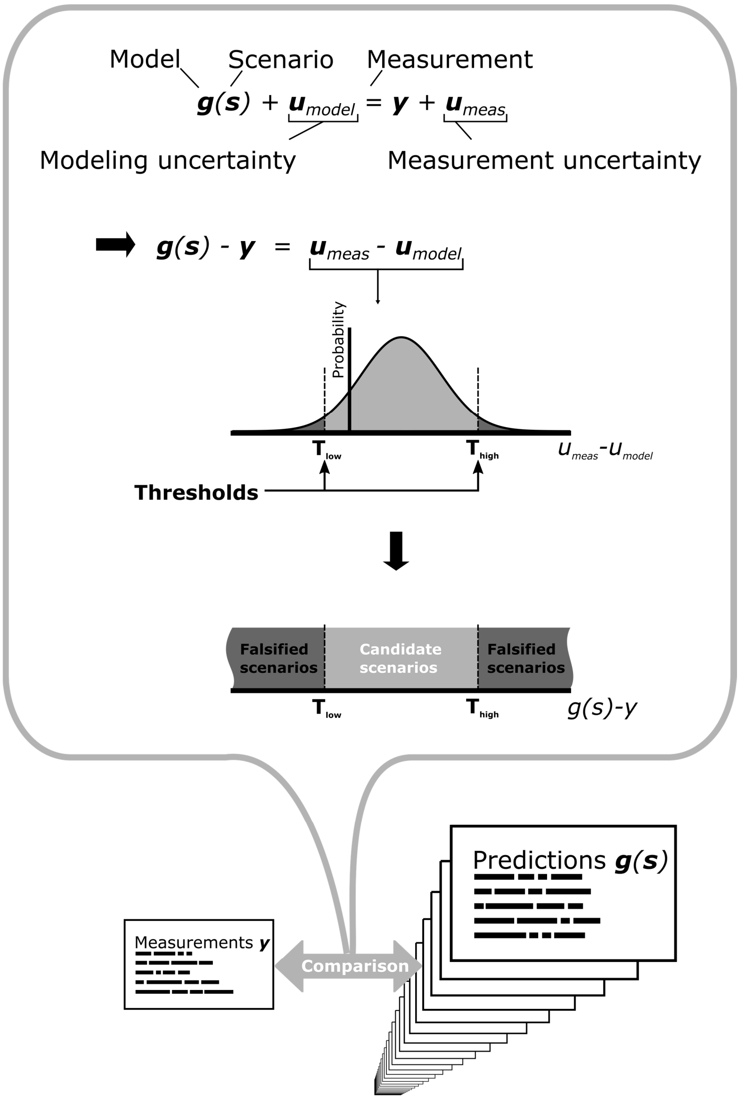


Figure 2 Schema of the falsification process

2.3 Uncertainty sources

Thresholds used to falsify scenarios are obtained using Monte-Carlo simulations to combine modelling and measurement uncertainties. Measurement uncertainties are due principally to the sensor resolution. Modelling uncertainties include those due to model simplifications and parameter uncertainties. Model simplifications are the consequence of inevitable hypotheses made during development of the mathematical model. For example, in the electric network model used for this paper, resistors are considered to be perfect, without heat dissipation. Parameter uncertainties are due to errors in the parameter values.

For this study, to facilitate comparisons of the results obtained using both networks, the same model and measurement uncertainties have been chosen. It is clear that, in reality, these uncertainties are not the same. They are smaller for the electric network. Measuring the current in a wire is more precise than measuring flow in a pipe. Ohm’s law is also more realistic than the Hazen-Williams relation. For the sensor resolutions (measurement uncertainties), a uniform distribution with lower and higher bounds at ±2% is used.

For uncertainty due to model simplifications, the assumption is made that the hypotheses used in the mathematical model lead to a systematic overestimation of the flow. Various factors are the source of this overestimation, such as friction and turbulence that occur at bends and fittings. For this study, this simplification uncertainty is estimated to be between -30% and 5%. Due to a lack of more precise information, an extended uniform distribution (Goulet and Smith, 2011) was assumed between these two bounds.

For this study case, only the nodal demand is considered for parameter uncertainties. The influence of the other parameters, such as the pipe diameter, roughness, node elevation for hydraulic network and resistance for electric network, on the simulation results is lower in comparison to the nodal demand, so they can be neglected.

The demand at each node (nodal demand) is unknown; only the demand of the entire network (global demand) is known. For the two networks, the nodal demand is modelled using an exponential distribution with the mean of the distribution equal to the global demand divided by the number of nodes. The global nodal demand used is 0.00694 (cubic meters per second for the hydraulic network and Amperes for the electric network).

3. Results

The first point is to show the direct similarity between the hydraulic and electric network models. This is done by comparing the flow and the current obtained by simulating leak scenarios using the hydraulic and electric models. Figure 3 shows these results for one sensor location. The horizontal axes refer to the individual leak scenarios. The vertical axes display the flow in cubic meters per second for the hydraulic model and the current in Amperes for the electric model.

These results show that the shapes of the two data plots are comparable. In both cases, peaks and valleys are obtained for the same scenarios. This shows that the behavior of the two models is similar. The next step is to show that similarity is maintained throughout the process of model falsification.

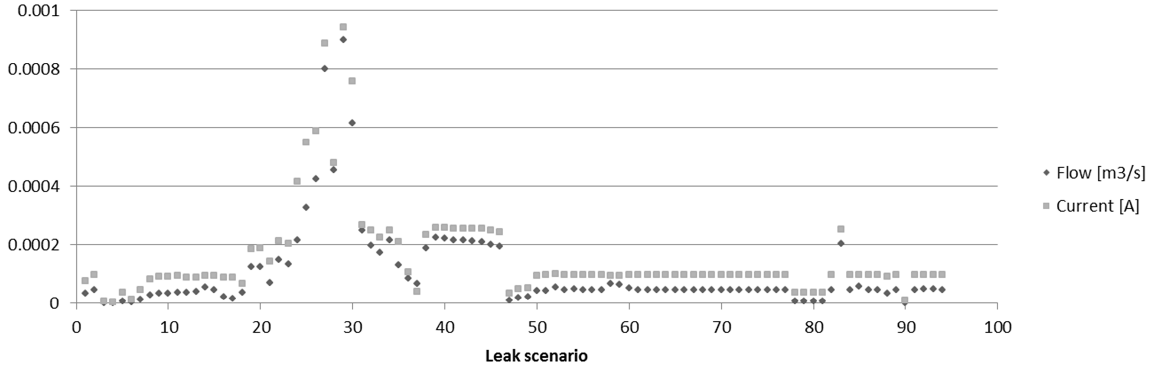


Figure 3 Comparison of values simulated at one sensor location for each leak scenario

The hydraulic and electric models have both been used for leak/loss detection using model falsification. Figure 4 shows results obtained for four leak locations (with the same leak intensity). Each leak location is studied through hydraulic and electric models. Results are given for the electric model on the left side and for the hydraulic model on the right side. The leak intensity used in these experiments is 125 l/min (0.002083 m^3/s) for the flow and 0.002083 A for the current.

The leak position is displayed in each result by four arrows. The sensor positions are represented by black squares. The white circles are the demand nodes and the grey lines are the pipes. The dark circles show positions of the candidate leak scenarios. The candidate leak scenarios define areas called “leak regions”. They are similar for the four examples. Although results differ by some nodes, the general form of the leak regions are the same.

The analysis of the results for the 94 leak locations shows that, on average, 85 percent of candidate scenarios obtained with the hydraulic network are the same as those obtained with the electric model. On average there are only seven scenarios that differ when comparing the electric and hydraulic model behaviors through model falsification. They diverge because of the differences of the model used for electric network (Ohm’s law) and the hydraulic networks (Hazen-Williams).

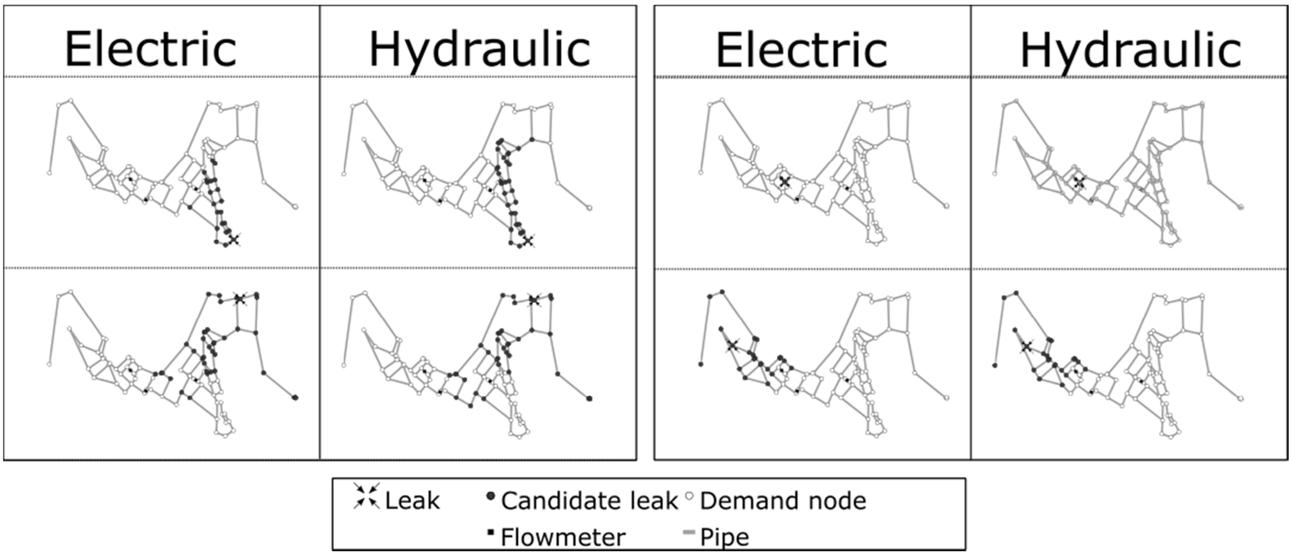


Figure 4 Comparison of candidate scenarios resulting from leak detection for electric and hydraulic network

Figure 5 shows the comparison of the expected identifiability for the hydraulic and electric models. Expected identifiability indicates the performance of the diagnosis. It is a cumulative distribution function that represents probabilities of obtaining certain numbers of candidate scenarios.

The vertical axis gives the probability, and the horizontal axis gives the number of candidate scenarios that are expected for the given probability. These curves are obtained for a leak intensity of 125 l/min (0.002083 m^3/s) for the flow and precisely 0.002083 A for the current.

These curves show that the diagnostic performance is nearly identical for the two models. For example, there is a 95% probability of identifying less than 53 candidate scenarios using the electric model and 52 for the hydraulic model. For a 75% probability, the number of candidate scenarios is 42 for the electric network and 39 for the hydraulic network. For a 50% probability, the number of expected candidate models is 24 for both networks.

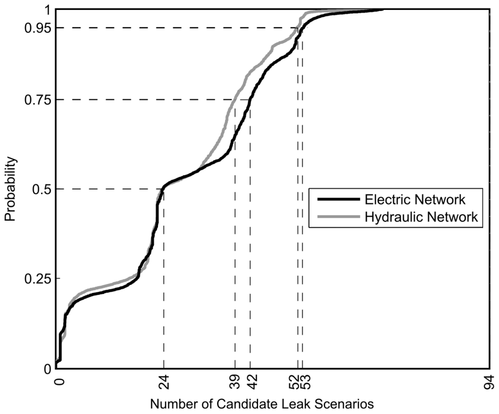


Figure 5 Comparison of the expected identifiability using the electric and hydraulic network models

4. Discussion

This paper studies the similarities between a model of an electric network and a model of a hydraulic network through model falsification. The study shows that even when the models have varying characteristics of underlying physical principles (the electric model is linear and the hydraulic is non-linear), results, when using model falsification, are similar.

Electric networks may be used in further work for studying and testing the leak detection methodology. A potential advantage is that results and conclusions obtained using a small-scale laboratory apparatus can then be generalized to full-scale hydraulic networks.

The use of electric networks for studying the behavior of water distribution networks may have some limitations. For this study, parameter uncertainties were neglected because, in this case, they have little influence when compared with the effects of other uncertainties. However, in cases where uncertainties associated with certain parameters cannot be neglected, the similarity between the electric and hydraulic networks may decrease.

Another aspect not studied in this paper is the similarity when using time dependent simulations. Steady-state simulations are assumed in this paper. It is unclear if behavior remains similar when parameters vary with time. For example, an electric network would react nearly instantaneously to a perturbation while a hydraulic network would have more time-dependent behavior when it is perturbed by an event such as a pipe burst.

5. Conclusion

Analyses of the results lead to the following conclusions.

Simulation of results show that the behavior of electrical resistance networks with local current loss is similar to the behavior of water distribution networks with leaks.

This similarity extends to current loss diagnostic behavior when using model falsification. On average, 85 percent of the candidate scenarios obtained by model falsification are identical across both network types. Furthermore, the expected identifiability shows that diagnostic performance is the same.

Due to such similarities, conclusions obtained through studying electrical networks are applicable to water distribution networks.

Measurements performed on electrical lab networks have the potential to illustrate the efficiency and the adaptability of the leak detection methodology for full-scale applications by varying the topography and the size of the network.

Further work will use comparison of electrical laboratory networks with full-scale hydraulic networks to obtain better approximations of uncertainties in fluid networks.

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