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An electrical network for evaluating monitoring strategies intended for hydraulic pressurized networks

Gaudenz Moser [a], Stephanie German Paal [a], Diane Jlelaty [b], Ian F.C. Smith [a,*]

[a] Applied Computing and Mechanics Laboratory (IMAC), School of Architecture, Civil and Environmental Engineering (ENAC), Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland

[b] Georgia Tech., Atlanta, USA

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ABSTRACT

This paper presents a study of similarities between electrical and hydraulic pressurized networks. The primary objective is to examine whether or not it is possible to use electrical laboratory networks measuring voltage to study leak-region detection strategies measuring flow in water-distribution networks. In this paper, the strategy used to compare the networks is error-domain model falsification, a previously developed methodology for data interpretation that combines engineering knowledge with models and data to enhance decision making. Simulation results obtained for a part of the water-supply network from the city of Lausanne are compared with an analogous electric network. The electrical network is simulated using resistors to mimic the pipes. The consequence is that the electrical model is linear. The resistance values are obtained by computing the hydraulic resistance for each pipe, given by the Hazen-Williams equation. The compatibility of the two networks is evaluated through simulations in three ways: (1) comparing flow predictions obtained by simulating several leak scenarios; (2) comparing the expected identifiability (performance) of the two networks; and (3) comparing sensor placement configurations. The analyses show that even though the models have varying characteristics of underlying physical principles (the electrical model is linear while the hydraulic model is non-linear), the results are within generally accepted engineering limits of similarity (10%). This indicates that measurements on electrical laboratory networks have the potential to illustrate the efficiency and adaptability of leak-detection methodologies for full-scale water-supply and other pressurized hydraulic networks. Finally, two electrical laboratory physical networks, including an electrical model of part of the water network in Lausanne, were constructed and used in case studies to illustrate this adaptability.

1. Introduction

Fresh water is a key resource in sustainable development. Clean water needs to be preserved and this includes waste prevention. The annual cost of the World's fresh water supply has been estimated to be 184 billion USD [1]. Approximately 5% of this cost (9.6 billion USD) is the consequence of leakage. This represents an average of 20% of clean water supply. These numbers show that there is a need to improve management of fresh-water supply networks. While efficient monitoring systems for leak detection can enhance knowledge, such systems also require advanced sensor-based diagnostic methodologies in order to realize their potential.

Leak detection techniques are usually indirect since measured quantities are used to indirectly infer water loss. Techniques include noise monitoring, pressure monitoring and flow monitoring [2]. The principle of noise monitoring is to capture the noise signal caused by the water flowing through a leak. Other techniques involve measuring variations in the hydraulic state (pressure and flow) due to the presence of a leak. This category can be separated into two groups. The first is transient-based; these techniques use measured transient signals (usually the pressure) to detect leaks [3–7].

The second group is based on the study of steady-state regimes. These techniques can be based on comparisons of measurement with predictions obtained by simulating hydraulic numeric models. Finding predictions corresponding to measurements can be formulated as optimization tasks [8,9] and by Bayesian inference [10–13]. Weaknesses of these kinds of data-interpretation approaches has been identified by Goulet and Smith [14] and later by Pasquier and Smith [15]. They have shown that approaches such as Bayesian inference and least-square regression may lead to

* Corresponding author.
E-mail address: Ian.Smith@epfl.ch (I.F.C. Smith).

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biased identification and prediction with the presence of systematic uncertainties and subsequent unknown correlations, particularly when extrapolating.

Another strategy that can be used to interpret measurement data is model falsification. This principle was first applied to leaks by Robert-Nicoud et al. [16]. Model falsification was developed further by Goulet and Smith [17]; they developed a methodology called error-domain model falsification for infrastructure diagnosis. This methodology was applied to leak-region detection in a preliminary study by Goulet et al. [18] and another study extended this to specific sensor locations [19,20]. Model falsification typically results in sets of candidate-leak locations that form one or more candidate regions for subsequent investigation using techniques such as acoustic emission.

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. No previous research has been found to address this challenge in combination with an explicit representation of several sources of measurement and modelling uncertainties.

This paper describes a proposal for electrical resistance networks, measuring voltage, that have behavior characteristics which are similar to water distribution networks, measuring flow, and are less complex to build. The paper is a greatly extended version of a previously published conference paper [21]. Through presenting a more extensive range of results, this study goes into much further detail regarding the usefulness of an electrical analogy for water-supply networks. Furthermore, several leak intensities, leak locations and sensor configurations are evaluated for two electrical case studies.

Electrical parallels have already been used by several researchers. Techniques to reduce water distribution networks into a simpler equivalent network have been developed [22,23]. Oh et al. [24] reviewed the application of electrical circuits for the analysis of pressure-driven microfluidic networks. Aumeerally and Sitte [25] used electrical networks to model the flow-rate of micro-channels. However, no work has investigated the range of validity of this analogy in the presence of uncertainty.

Electrical analogies have also been used in fields other than hydraulics. Various systems have been modelled by electrical networks such as DNA structures [26–28], stomata networks [29] and tidal stream power resources [30]. However, no previous research has employed electrical networks to test monitoring strategies, such as leak-detection methodologies in water-supply networks.

This paper compares the behavior of a direct current (DC) electrical network model with a hydraulic network model used for leak-region detection using the error-domain model falsification approach for data interpretation. First, the range of validity of this analogy is evaluated in Section 2. Direct similarities are shown by comparing results obtained from simulations of both models. These models are then used to demonstrate similarities through data interpretation in Section 3. Then, two case studies are presented in Section 4 to illustrate the advantage of constructing electrical laboratory networks (Fig. 1). Ultimately it is shown that electrical networks are viable for use as physical surrogates for hydraulic pressurized networks when designing monitoring strategies.

2. Methodology

In Fig. 1, an outline of this study is presented. The purpose of the study is to show similarities between the behavior of hydraulic and electrical network models and to test and evaluate the diagnostic methodology presented in this paper with electrical case studies. In this section, the analogy between electrical and hydraulic networks is presented. This analogy is then used to build a model of an electrical network based on the model of a hydraulic network. Following this, the principle of model falsification as it is applied to leak-region detection is described.

2.1. Hydraulic/electrical analogy

Fig. 2 illustrates the analogy comparing flow in a pressurized pipe with direct current (DC) through a resistor. The Hazen-Williams relation (left) is an empirical relation:

$$\Delta H = 10.674C^{-1.852}d^{-4.871}LQ^{1.852} = R_{Hydraulic}Q^{1.852} \quad (1)$$

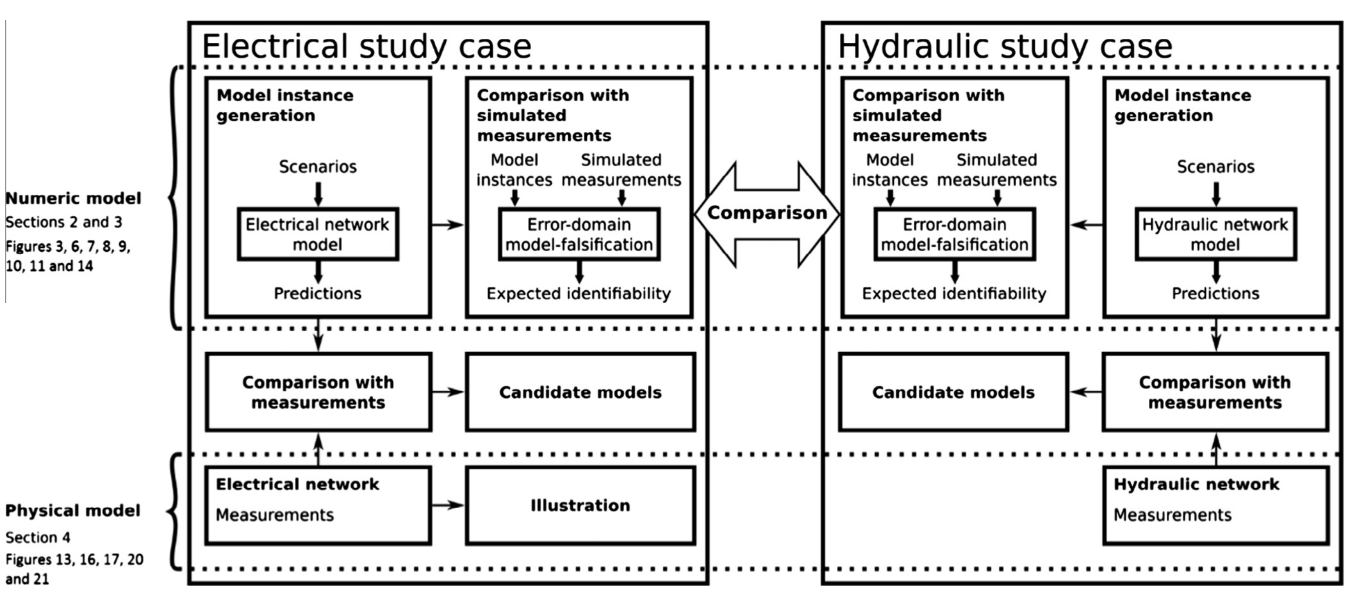

Fig. 1. Flowchart of this study of the electrical-hydraulic analogy. Relevant sections and figures in this paper are noted on the left.