

The differential perturbative method applied to the sensitivity analysis for waterhammer problems in hydraulic networks

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Abstract

The differential perturbative method was applied to the sensitivity analysis for waterhammer problems in hydraulic networks. Starting from the classical waterhammer equations in a single-phase liquid with friction (the direct problem) the state vector comprising the piezometric head and the velocity was defined. Applying the differential method the adjoint operator, the adjoint equations with the general form of their boundary conditions, and the general form of the bilinear concomitant were calculated for a single pipe. Considering that any hydraulic network can be built by connecting different components (reservoirs, valves, pumps, tees, etc.) through pipes, the adjoint relationships for any component, as well as the final contribution to the bilinear concomitant, were calculated. Moreover, an analogy was established in which transmission and reflection coefficients can be derived for any adjoint component. The importance or adjoint function was analyzed when the piezometric head or velocity at a given position and time is chosen as the response functional. In this case, it is shown that the importance function is represented by delta-functions travelling along the hydraulic network with the propagation speed. The calculation of the sensitivity coefficients takes into account the cases in which the parameters under consideration influence the initial condition. For these cases, the calculation can be performed by solving sequentially two perturbative problems: the first one is non-steady, while the second one is steady, with an appropriate selection of a weight function coming from the unsteady perturbative problem. The discretized adjoint equations and the corresponding boundary conditions were programmed and solved by using the method of characteristics. As an example, a constant-level tank connected through a pipe to a valve discharging to atmosphere was considered. The corresponding sensitivity coefficients due to the variation of different parameters by using both the differential method and the response surface generated by the computer code WHAT, solver of the direct problem, were also calculated. The results obtained with these methods show excellent agreement. © 2001 Elsevier Science Inc. All rights reserved.

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1. Introduction

The analysis of waterhammer transients plays an essential role in diverse areas such as hydroelectric projects, pumped-storage schemes, water supply systems, nuclear power plants, oil pipelines and industrial piping systems [1]. In nuclear power plants, for example, various operating transients in the heat transport system can lead to significant pressure changes, which must be taken into account in the design for a safe operation [2].

Coupled to any transient calculation, there is a necessity of estimating the influence of changes in the parameters on a defined response based on the obtained solution. This task, known as sensitivity analysis, can be performed by running repeatedly the computer code used in the calculations for different values of the parameters; in this way, a response surface is generated. However, this method requires time consuming calculations when many parameters are involved.

A different approach to perform the sensitivity analyses are the perturbation methods, which have been extensively used in reactor physics through the concept of the importance function [3–5]. The application of perturbation methods to the thermal-hydraulics field has been first proposed by Oblow [6] by using the so-called differential method; since then, it has been successfully extended [7]. The differential method has the following advantages:

- (i) The sensitivity analysis can be performed without choosing a priori any parameter.
- (ii) The calculations are faster and more efficient, since only one additional set of linear equations needs to be solved for a prescribed response.

The differential method is restricted to the linear behavior of the response surface in the vicinity of a specific design point, this being the main disadvantage.

The purpose of this paper is to outline the development of the sensitivity theory for a general waterhammer problem. The organization of this paper proceeds as follows: in Section 2 the theory for a general waterhammer problem is presented. In Section 3 the boundary conditions for the adjoint problem and the bilinear concomitant are derived, taking into account that a hydraulic network can be built with pipes connecting components. In Section 4 some response functionals are analyzed, namely the local instantaneous piezometric head and velocity, and the adjoint reflection and transmission coefficients are calculated for different components. In Section 5 the numerical procedure (i.e., the method of characteristics) used to solve the direct and adjoint problems, as well as the numerical difficulties, is outlined. In Section 6 a simple example is presented, showing an application of the methodology.

2. Theory for a general waterhammer problem

2.1. Direct equations

Consider the general one-dimensional waterhammer equations in a single-phase liquid with friction [8], in which the convective terms are neglected:

$$m_1 \equiv \frac{\partial H}{\partial t} + V \sin \theta + \frac{a^2}{g} \frac{\partial V}{\partial x} = 0, \quad (1)$$

$$m_2 \equiv g \frac{\partial H}{\partial x} + \frac{\partial V}{\partial t} + \zeta \frac{V|V|}{2D} = 0, \quad (2)$$

where H is the piezometric head, V is the fluid velocity, a is the wave propagation speed, D is the pipe diameter, θ is the pipe inclination angle, g is the gravity acceleration and ζ is the Darcy friction factor (function of V).

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