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Finite dimensional models of the hydraulic hammer effect and solar tower control

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ABSTRACT

The occurrence of traveling shock waves associated to the sudden opening or closing of a valve, known as the hammer effect, is important from the perspective of control design because it imposes an upper bound constraint on the maximum bandwidth achievable for the controlled system. This article addresses the problem of characterizing hydraulic hammer effect of the heating fluid in a solar power tower. The transfer function that relates the increments of the pressure inside the pipe and the fluid velocity is computed, as well as its poles and zeros. In this way, it is possible to obtain finite dimensional linear approximations for this transfer function with a prescribed complexity. As an application, the traveling waves of pressure and velocity of a fluid used for temperature control in a typical solar tower circuit are simulated.

1. Introduction

The objective of a solar power plant is to capture solar energy in a heat transfer fluid (such as molten salt) and to store it in thermal form in a tank from where it can be extracted to feed a steam generator that is connected to a conventional turbo-generator in order to produce electrical power. For that sake, the molten salt fluid is taken from a “cold” storage tank and pumped through a flow control valve and the tower receiver, where its temperature is increased due to the concentrated sun radiation, after which it is stored in a “hot” tank. The molten salt fluid is extracted from the hot tank, passes by the steam generator and goes to the cold tank.

The salt valve is driven by a flow controller that adjusts the salt flow such as to keep the salt temperature at the receiver outlet close to the desired level. In the plant considered, the fluid flow is forced by a constant velocity pump and the flow is changed by a control valve. If the rate of change of the valve is too high, the phenomena known as hydraulic hammer (HH) may be induced.

The hydraulic hammer [1] is a phenomena that develops in closed pipes and consists of multiply reflected traveling pressure waves that are induced when the fluid flow is suddenly interrupted by an obstacle, such as a valve that closes. Therefore, the HH effect imposes an upper bound on the bandwidth of a feedback controller, that drives the valve on the temperature regulation controller on solar power towers.

The problem of modeling the HH is thus an important one, not just for mechanical design, but to establish the specifications of controllers that use the equipment as well since it imposes a limit on the achievable closed-loop bandwidth.

1.1. Literature review

Due to its practical importance for different kinds of plants, the hydraulic hammer effect has been the subject of a wide literature. Although there are no published references that specifically concern solar thermal plants, much of the available results may however be applied to this case.

This section presents a literature review that is not exhaustive, but only aims at covering the basic points addressed in the present article. In addition to references that concern the mathematical modeling of the physical phenomena that underly HH, other references related to the propagation of shock waves have been inserted because they suggest mathematical approaches that are shown in this work to be useful to the problem at hand. Fur-

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thermore, a pointer to the system view literature for distributed parameter plants has been included [8].

In [1] a comprehensive overview of both historical developments and present day research and practice in the field of hydraulic transients is presented, including mass and momentum equations developments for one-dimensional hydraulic hammer flows. The above mentioned paper also discusses numerical solutions for two-dimensional problems, boundary conditions and transient analysis software. The classic analysis of the pressure wave propagation after sudden valve closure (hydraulic hammer), using the Newton Law, is treated in Fluid Mechanics introductory books like [2,5]. Recent fluid mechanics advances in unsteady pipe flow friction modeling and hydraulic-hammer wave attenuation, shape and timing are treated for instance in [9–11]. These articles report computational results for pressure wave curves, that are obtained from numerical solutions for unsteady friction models in transient pipe flow. Computational results from the numerical models are compared with results of measurements performed in a laboratory apparatus. A recent Ph.D. thesis [12] solves hydraulic hammer hyperbolic partial differential equations by the method of characteristics and compares these solutions with the results obtained in an experimental apparatus, in studies on dynamics of unsteady pipe flow involving backflow prevention assemblies.

Rigorous physical model solutions obtained from coupled hyperbolic partial differential equations using transfer functions for infinite dimensional systems and complex analysis theory can be found in [4,8]. In the first one, a book about modeling and control of hydro-systems, transfer functions, poles and zeros locations are obtained to analytically solve the linearized Saint-Venant Equations for hydraulic delivery open canals. In the second one, a tutorial paper, transfer functions for some other representative examples of infinite-dimensional systems are derived along with some relevant theoretical issues like finding poles, zeros and partial fraction expansions for irrational transfer functions.

Analysis of the HH effect, relying either on numerical integration of the basic equations [14], or combining it with experimental measurements [15] are also available.

In the same line of research of the present work, the article [13] reports the use of an analytical algorithm for solving the unsteady, one dimensional, hydraulic hammer model, claiming that this algorithm allows to estimate the instantaneous head at any point of a single pipeline and adds, quoting, that the model was solved by mean of the Laplace Transformed application and the anti-transforming procedure into the complex field. The so-called general expression for the pressure (in time along the pipe) is included, without proofs or references. Although not explicitly addressing the HH effect, but bearing in common with this article a system view, the recent book [16] focus on mathematical modeling of wave propagation on processes involving transport of mass and/or energy, that are modeled by hyperbolic partial differential equations.

1.2. Contributions and structure

This article addresses the modeling of the HH effect using the methods of systems theory. As such, a transfer function that relates the increments in pressure inside the pipe and fluid velocity are obtained. The problem of building an approximate finite dimensional linear approximation for the HH transfer function with an *a priori* prescribed order is solved. This solution relies on the computation of the poles and zeros of the exact transfer function. As an application, the HH pressure waves induced by a control valve are computed.

After this introductory section in which the problem is introduced, together with a literature review and a qualitative discussion, the basic equations of hydraulic hammer are presented in Section 2. Section 3 presents the solution for the linear model with friction along with the related transfer function. Section 4 describes how to compute the poles, zeros and partial expansion series for the transfer function presented earlier. Using the technique exposed, a finite dimensional model of the HH is used in Section 5 to compute the pressure wave in response to the control valve movements in the temperature of a solar power tower. Finally, Section 6 draws conclusions.

Table 1
Model parameters.

Parameter	Value	Units
L	20	m
D	0.1	m
ρ	1000	kg/m^3
f	0.03	–
c	1200	m^3/s
P_0	0.2	MPa
V_L	2.0	m/s

2. The hydraulic hammer equations

The hydraulic hammer (or, more generally, fluid hammer) effect is a pressure traveling wave caused when a fluid (usually a liquid but sometimes also a gas) in motion is forced to stop or change direction suddenly (momentum change). A hydraulic hammer commonly occurs when a valve closes suddenly at an end of a pipeline system, causing a pressure rising wave that propagates in the upstream current fluid and along the pipe.

Let $t(s)$ denote time and $x(m)$ denote the position along the pipe. The hydraulic hammer effect can be simulated by solving the following partial differential equations [1]

$$\frac{\partial p}{\partial t} + \rho c^2 \frac{\partial v}{\partial x} = 0 \tag{1}$$

$$\frac{\partial v}{\partial t} + \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{f}{2D} v|v| = 0, \tag{2}$$

where p is the pressure inside pipe, v is the fluid velocity, ρ is the fluid density, assumed to be constant, $B = \rho c^2$ is the equivalent bulk modulus and f is the friction factor. The steady-state is given by

$$\frac{\partial v}{\partial x} = 0 \tag{3}$$

$$\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{f}{2D} v|v| = 0. \tag{4}$$

Choosing $v(L, t) = V_L$ and $p(0, t) = P_0$ as boundary conditions yields

$$v_{ee}(x) = V_L, \tag{5}$$

$$p_{ee}(x) = P_0 - \rho \frac{f}{2D} V_L^2 x. \tag{6}$$

The parameters considered in this article are given in Table 1. Solving Eqs. (1) and (2) for a sudden change in the fluid velocity at the pipe end, $v(L, t)$ boundary condition, it is possible to predict the pressure wave in the fluid.

3. The HH transfer function

The linearized equations that relate the increments p of pressure inside the pipe, and v of fluid velocity in order to describe the HH effect are

$$\frac{\partial p}{\partial t} + \rho c^2 \frac{\partial v}{\partial x} = 0 \tag{7}$$

$$\frac{\partial v}{\partial t} + \frac{1}{\rho}\frac{\partial p}{\partial x} + \beta v = 0, \tag{8}$$

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