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Experimental setup for measuring roll waves on laminar open channel flows

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ABSTRACT

Experimental studies on open channel flows are explored mostly because of their importance in validating analytical and numerical models. Although steady flows are usually measured and explored, difficulties arise in the precise execution of this task when the free surface becomes oscillatory. This paper presents a methodology for measuring a particular non-stationary phenomenon that occurs under specific conditions, namely, roll waves. Limited data exists in literature on roll waves. The objective of this work is to contribute to this database and to describe a useful experimental method for measuring roll waves. Based on some well-known literature experiments, an experimental setup was designed to achieve the free surface flow of a viscous fluid in a steady and uniform configuration. The flow was set to generate roll waves and controlled disturbances were applied at the inlet to develop roll waves. These waves were then measured using a photometric device based on a light absorption technique. The wave profiles for different flow configurations are presented. Experimental results were compared with numerical simulations to assess the validity of the measurements taken.

1. Introduction

Free surface flows can occur in many forms in industrial and environmental processes and they have therefore been a subject of much interest in fluid mechanics studies. Rivers, seas, sewers, channels, and drainage systems are a few examples of situations where this particular hydraulic model can be used. The characterization of flow properties using physical and mathematical models is necessary in many applications, such as for designing structures, better predicting flow behavior, and applying safety policies.

The precise study of free surface flows based on experimental results is of significant importance for understanding transitional flow. The occurrence of non-stationary phenomena on free surfaces implies that infrastructure projects should take additional considerations into account to guarantee their safe functioning. Among the possible phenomena that could affect free surface flow, roll wave instabilities are of interest, as discussed in this paper. These instabilities can usually be seen on artificial channels (such as spillways) where turbulence occurs. They are configured as periodic fronts, and present hydraulic jump characteristics that propagate downstream at constant velocity. Roll waves are different from normal gravity waves as they result from the amplification of flow disturbances. In laminar flow, especially for non-Newtonian fluids, they are more visible and present higher amplitudes (of the same order of magnitude as the flow) [1–3]. Because of this oscillatory configuration, measuring their free surface inclination and elevation is rather difficult. The inherent difficulty of this task has resulted in a lack of data for the calibration and/or validation of numerous roll wave models and has therefore raised the interest of researchers in the scientific community.

The work of Kapitza [4] is among the first in this area where this task was executed successfully. Kapitza [4] conducted important experimental work by collecting free surface information from film flows using the shadowgraph technique. This technique, which is still used by some researchers, has great advantages in terms of flow visualization, despite the fact that it is less precise than some other techniques [5,6].

Many techniques rely on the Beer–Lambert law to detect the surface elevation, once the light properties of a fluid are known. As shown by Barter et al. [7], it is possible to acquire both the inclination and elevation of the free surface, if necessary, by

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adapting the Beer–Lambert law and by using a two-dimensional photodetector. Although capillary waves were tested by Barter et al. [7] (low amplitude and surface inclination), they remark that a possible adaptation for larger-scale tests could be achieved. A digital solution for the circuitry design was proposed 1 year later by Barter and Lee [8], when they established a method for acquiring surface elevation information using the signal power spectrum. Barter and Lee [9] later showed that capillary waves could be represented efficiently by that method over time and space (over the measurement window) with good precision. The results show that the measurement techniques can employ not only circuitry design but also signal processing techniques to obtain the required information.

Another useful technique to have spatial and temporal measures is the light-induced fluorescence (LIF) technique. This method has been used extensively to measure waves on open channel flows, especially roll wave instabilities and capillary waves. In Liu et al. [10], Liu and Gollub [11] experiments, a water solution of glycerin was tested and results concerning the harmonics frequencies of roll waves forced by the capillary effect were obtained. The apparatus used by those researchers was set up over an inertial bench so that experiments were isolated from external disturbances which could mislead wave formation and measurements. LIF has become the preferred measurement technique because of its easy visualization [12].

Mouza et al. [13] used a more direct and relatively simple measurement system for steady film flows, and measured water flows up to 2 mm high using the light absorption technique. This technique is rather intuitive, is easily implemented, and is very low cost compared with more complex measurement systems. They did, however, remark that measurements (flow height) made with this system when the free surface presents steep waves require additional care and measurements cannot always be assured.

A review of film flow measurement systems up to the end of the 1990s is provided in the work by Shedd and Newell [14], which discusses the most popular techniques of that time and their advantages and disadvantages. Currently, many researchers are looking for light-based measurement systems that can be used with signal processing software because of the possibilities offered by this combination.

In this work, we use the favorable properties of the light absorption technique [13], which is rather inexpensive and easy to operate. This method is adapted here for measuring roll waves on glycerin laminar flow over an open channel. The test bench is isolated from external disturbances and the steady flow is disturbed by a controlled nozzle system, as in the work by Liu et al. [10], Liu and Gollub [11]. Measurements are treated mathematically using a digital filter. In Section 2, a detailed description of the test bench for the roll wave experiments is provided, including the measurement system and calibration apparatus, based on the work by Mouza et al. [13]. An explanation is provided of the modifications adopted in the device for the measurement of steep traveling waves. In Section 3, results for three different roll wave experiments are shown and discussed. In Section 4, the experimental results are compared with a numerical simulation and the wave parameters are analyzed. Finally, in Section 5, some final considerations and perspectives are provided.

2. Experimental setup

The experimental apparatus (see schematic in Fig. 1.) was designed to generate surface instabilities using a known and controllable frequency, and to create a favorable domain for its stabilization as a roll wave. The following subsections summarize the main characteristics of each component in the experimental setup.

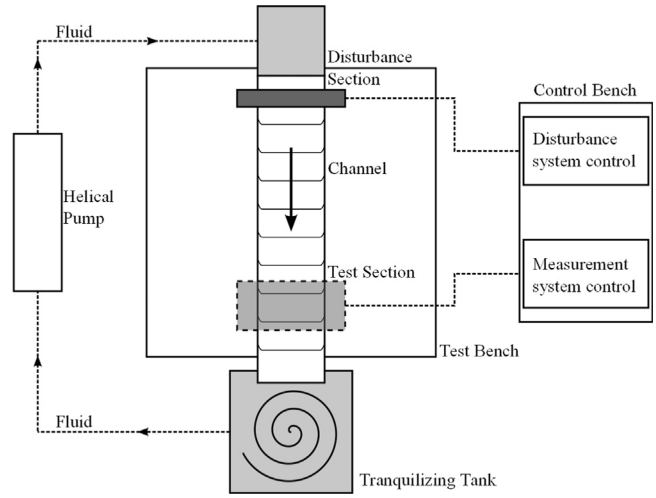

Fig. 1. Schematic diagram of the apparatus used. Drawing not to scale.

2.1. Test bench

The test bench was based on experiments by Liu and Gollub [11], who stressed that the test bench should be isolated from external disturbances. A high mass was therefore added to the bench, and anti-seismic vibration devices were installed at its base, in contact with the ground. In this way, disturbances to the bench from the pump, the movement of people, and other ground vibrations can be minimized, and vibrations in the channel installed over the bench can be reduced significantly [10,11]. The channel (0.30 m wide and 2.50 m long) is composed of a glass bottom (8 mm thick) and Plexiglas walls (15 cm high), which are installed securely over a metallic structure that allows the precise inclination of the channel (θ). The channel dimensions make it possible to ignore the side border effects as the mean flow height h_0 is much smaller than the channel width l ($h_0/l < 1$).

2.2. Pumping system

Glycerin, which is a highly viscous Newtonian fluid (dynamic viscosity $\mu \sim 900$ mPa s and fluid density $\rho = 1273$ kg/m^3 at 25 °C), was used as the test fluid. The fluid properties allowed for the flow conditions to be maintained in the laminar regime with a smooth free surface. Fluid flows over the channel and is collected at the outlet by a tranquilizing tank, where it remains before being sent back to the channel (thereby reducing bubble formation). A digitally controlled helical pump (pumping power 3300 watts), sends the fluid to the inlet tank with minimal friction. Measurements of the discharge rate were conducted using a high precision scale, bucket, and chronometer. The mean standard deviation for the discharge measurements from 0.1 to 1.9 l/s was 5%. The measurements were more accurate for discharges of 0.4 l/s (mean standard deviation of 3%) and less accurate for discharges of 2 l/s (mean standard deviation of 6%). This error is the same for the mean flow velocity u_0.

Although the fluid properties were monitored during each measuring sequence by rheometric testing, the viscosity decreased slowly after each experiment. A number of effects could have contributed to this variation, mainly because the setup was installed in an environment without climate control. The fluid reservoir was exposed to ambient temperatures of 30 °C (and higher) and an air humidity of 60–70%. The shearing effects on the pump could have led to the viscosity modifications mainly because the pump was designed for highly viscous fluids.