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Non-intrusive techniques to measure roll waves level evolving in a flume

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Abstract. An open-channel experimental set-up is presented in this paper as a tool for examining the presence of instabilities on free-surfaces flows of non-Newtonian fluid. When these flows occur in favorable conditions of inclination, discharge and rheological properties, the propagation of instabilities can evolve into a specific type of wave, known as roll waves. The experimental apparatus developed allows study of stabilized roll waves in many scenarios for non-Newtonian rheology fluids, thereby constituting a highly useful tool for the understanding and control of roll waves. The test fluid used in the experiments was carbopol gel which is rheometrically representative of the muddy material from natural disasters, such as mudflows. Two non-intrusive level measurement systems are proposed (ultrasonic transducer and laser-based absorption technique), and the efficiency of each technique is presented and discussed. Both methods presented relatively low-cost implementation, and calibration procedure assured the quality of the results. The results from the experimental set-up were in agreement in shape and amplitude.

keywords: roll waves; non-Newtonian fluid; measurement methods; ultrasonic technique; light absorption technique.

1. Introduction

From the hydrodynamics perspective, disasters resulting from floods, torrential lavas, volcanic lavas, waves generated by sudden or gradual rupture of dams and tailings dams, among others, are characterized as natural flows with free surfaces. They spread over large areas causing environmental and social impact resulting in material and life losses and a significant number of victims. In addition, in situations of favorable dynamics and rheology, we have seen the appearance of instabilities in free surface of these flows, namely, in pulsating regime that comes to increase the damage generated. These instabilities, as

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literature shows, can be amplified and stabilized, propagating as a wave train, known as roll waves, whose properties are closely linked to the rheological properties of the flowing fluid and flow dynamics [1-4]. In various locations around the world, such as New Zealand, China, Switzerland and Italy, the presence of roll waves was recorded and proven through measurements in various scenarios (in slopes, natural talwegs, avalanche corridors, dam spillways), both in situations of clean water flows (Newtonian fluids) and in hyperconcentrated flows (non-Newtonian fluids), in laminar or turbulent regimes [5, 6].

Researchers have sought a better understanding of the phenomenon, dealing with the problem globally, whether through proposals for new mathematical models, new numerical simulation techniques [7-10] or modern experimental techniques (non-intrusive) for measurement of these waves.

In terms of physical experiments, the work of [11] stands out for being one of the pioneers in gauging (amplitude and celerity) of roll waves in water, using intrusive equipment (P7D pressure transducer, Pace Engineering Company and a Wire Gage). [12] reported measurements of roll waves in Newtonian fluids of high viscosity (glycerin). [13] developed experimental apparatus capable of measuring roll waves using optical technique with laser-induced fluorescence. Some experimental work in the literature report also the appearance of roll waves in non-Newtonian fluids [14-15]. [16], more recently, measured amplitude of roll waves in Binghamian fluid through also non-intrusive technique (digital imaging). This way, the RMVP research group[2] has been making efforts in the development and the operationalization of a low-cost experimental apparatus capable of generating and measuring roll waves, as we can see in Figure 1, whether in experiments with highly viscous Newtonian fluids [17], or with non-Newtonian fluids (muds and aqueous solutions of carbopol). In cases of non-Newtonian fluids, the works have focused on experiments with mixtures of kaolinitic clay and water; clay, water and sand and also carbopol 996 gel, acrylic polymer widely used in the pharmaceutical industry, as it is transparent and behaves similarly to rheology of mud. [18], using clay concentrations, conducted tests for different concentrations in volume and observed that the mixture is characterized as Herschel-Bulkley fluid, extending previous work by [1, 2, 19]. [20] used carbopol 940 gel as rheological representative material of mud in experimental and numerical studies simulating tailing dam break.

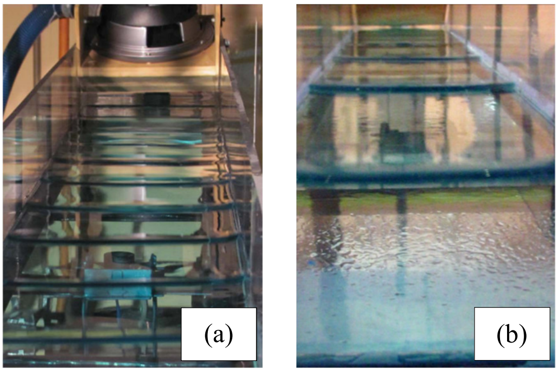

Fig. 1. Roll waves generated in an inclined channel [21]: (a) Highly Newtonian fluid (glycerin) - 3 Hz frequency; (b) non-Newtonian fluid (carbopol 996 gel) - 1.5 Hz frequency.

The experimental apparatus developed is precise and efficient regarding observation and measurement of free surface flow and capable of generating and controlling roll waves in non-Newtonian fluid flows, which has been contributing in advancing and strengthening the mathematical base and numerical studies of the phenomenon, in addition to filling a

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significant gap in the literature regarding experimental measures of the phenomenon under study.

Therefore, this article aims to present the experimental apparatus designed and constructed at the University, illustrating a case study of open channel flow using carbopol 996 gel with presence of roll waves whose amplitudes were measured by an ultrasonic transducer and photometric measurement.

2. Material and Methods

Figure 2 presents the experimental countertop scheme; Figure 3 illustrates the experimental apparatus in the laboratory of Hydrology and Hydrometry - LH2-UNESP - Ilha Solteira. The experimental apparatus consists of several sets, each built separately, with the objective of obtaining the best interaction and connection among them. For more information on the experimental apparatus see [17, 21]:

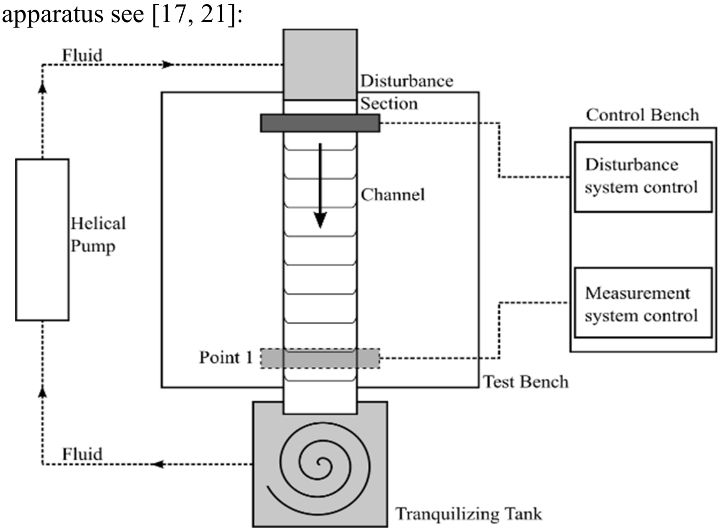

Fig. 2. Schematic of the experimental apparatus [21].

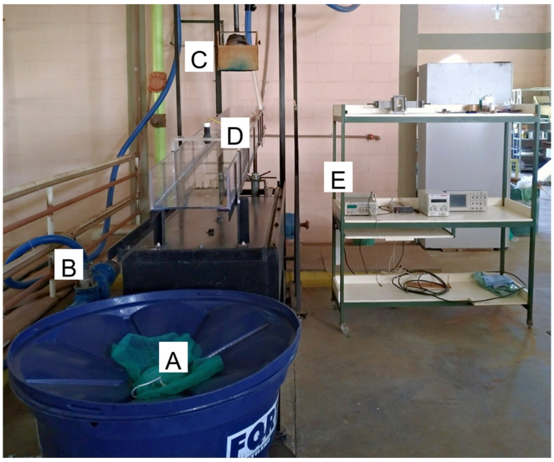

Fig. 3. Experimental apparatus, (A) Tranquilizing tank, (B) Helical pump, (C) Disturbance system, (D) Point of measure, (E) Disturbance system control/Measurement system.

- Channel – built with a glass bottom and acrylic walls, dimensions of $0.30 \times 0.15 \times 3.00$ m (width x height x length) and slope ranging from 0 to 25 degrees. In its initial part (upstream), a small reservoir was built to receive fluid discharge from the pump. Thus, the junction of the reservoir with the normal level of the flume is mild, so that in the inlet the fluid can smoothly enter in laminar regime. The channel sits on an inertial table;
- Inertial table – solid workbench in concrete and steel, designed for isolation of unwanted disturbances, absorbing external vibrations;
- Closed hydraulic circuit – movement in the system for fluid circulation comes from a hydraulic circuit adjacent to inertial table. This adjacent circuit begins on storage carbopol gel tank (tranquilization) and, using a hydraulic pump adapted to non-Newtonian and high viscosity fluids (positive displacement pump - Helical pump), the fluid is repressed for the upstream of the flume, establishing a closed circuit system;
- Disturbance system – formed by devices (speaker + diaphragm and function generator) that injected a narrow jet of air over the fluid, perturbing the flow with a controlled frequency;
- Level measurement system – its main feature is being non-intrusive (ultrasonic and laser systems) allowing for checking the result of the disturbing action of the air jet on the fluid in flow, that is, measuring the roll waves in transit;
- Test fluid – carbopol 996 gel, rheometrically tested (R/S Brookfield Rheometer) and fitted as a Herschel-Bulkley fluid (τ_c : yield stress, K_n: consistency index of the fluid and n: flow index);
- Level measurement system by ultrasonic waves – model RPS – 401A;
- Photometric level measurement system by luminous absorption – HeNe Laser with 633nm combined with a photodetector (818-SL).

The calibration of ultrasonic system is based on verifying the electrical voltage response of the transducer based on the distance of the apparatus from the free surface. Such distance is controlled by a micrometer (model Digimess), coupled to the transducer. Through the ratio of distance (transducer to free surface) to consequent electrical voltage, it is possible to construct the calibration curve and use its equation as relation between the voltage transformation and the free surface height at the moment of measurement in millimeters.

The photometric sensor calibration uses the same principle, changing some components of this system. At the time of calibration, a probe is used to control the level of fluid in the channel that corresponds to the optical path traveled by the beam emitted by the laser. Depending on the size of this path, the photodetector receives a light power less potent than that emitted by the laser, because part of the power is absorbed by the fluid, thus showing a voltage proportional to the level of the fluid. In this way, from the ratio of the liquid column (distance of the probe to the bottom of the channel) to the voltage detected by the photodetector, it is possible to construct a calibration curve and use its equation as relation between the electrical voltage transformation and the free surface height at the moment of measurement in millimeters.

The experiment was carried out with the channel inclined in 5 degrees and a flow rate of carbopol 996 gel ($\tau_c = 0.39$ Pa, $K_n = 0.15$ Pa.s$^{\mathrm{n}}$, $n = 0.699$) of 0.45 L/s (pump rotation of 475 RPM), uniform laminar flow depth (without presence of roll waves) of $6\mathrm{x}10^{-3}$ m, mean flow velocity of 0.25 m/s and free surface velocity of 0.32 m/s.

Initially, flow rates were measured using the gravimetric method, with average flow rate defined based on 10 samples. After that, a uniform flow depth was measured through the ultrasonic system and, from its parameters, the mean flow velocity was determined. For comparison purposes and in order to validate the results, the superficial speed was determined by the average of 10 measurements of the travel time of a float on the free surface between two fixed stations of the flume. Experimental errors are presented in Table 1.

The uniform flow was disturbed at the upstream of the channel at a frequency of 1.5 Hz. This disturbance was enough to produce stable roll waves (with maximum amplitude and length) at 1.5 m from the disturbance point, as indicated in Figure 2, in which the measurements were taken (Measurement Point 1).

Table 1. Uncertainties of the flow properties measured.

Instrument	**Measured quantity**	**Uncertainties**
Balance	Mass (g)	$\pm$ 0.1
Digital Chronometer	Time (s)	$\pm$ 0.2
Flow properties	**Measurement units**	**Uncertainties**
Free surface velocity (u_s)	(m/s)	$\pm$6.4%
Discharge (Q)	(m^3/s)	$\pm$ 7.3%
Mean flow velocity (u_0)	(m/s)	$\pm$9.0%

3. Results and Discussions

In Figure 4, we observe that the waves measured present features of roll waves: steep waves, with well-defined amplitude and length, typical shock waves, in agreement to the results observed by [17] with pure glycerin experiments, and similar to waves (roll waves in water) measured by [11] in flume and [13].

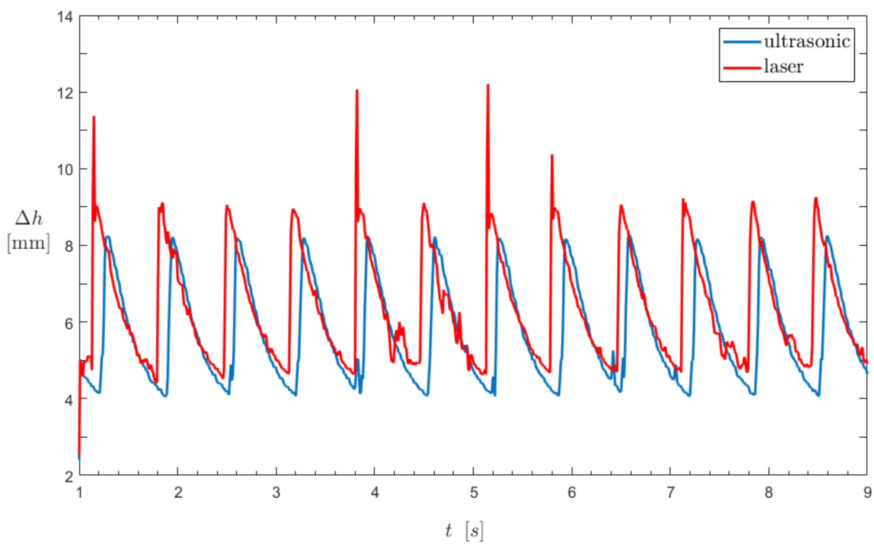

Fig. 4. Comparison between gaugings (raw data) with photometric system and ultrasonic system (carbopol 996 gel, $f = 1.5$ Hz).

The measured waves present amplitude of $(4.18 \pm 0.11)\text{x}10^{-3}$ m with a period of 0.67 ± 0.04 s. Moreover, the dominant frequency for the roll waves is the same as the disturbance imposed, as shown in Figure 5. Based on it, it is possible to define this as the fundamental frequency for the phenomenon $f = 1.5$ Hz. Regarding the comparison between laser and ultrasonic systems, the concordance in the amplitude and wave period was observed, with a minor displacement of average level value justified by the systematic errors of each measurement method. Furthermore, the measurements carried out with photometric system present "lost signal" in the crest of some waves. It is worth mentioning that this happened exactly at the steepest part of the wave (shock region). On the other hand, for measurements with ultrasonic system, the "lost signal" happened at wave trough, but with less repetitions when compared to measurements by laser.

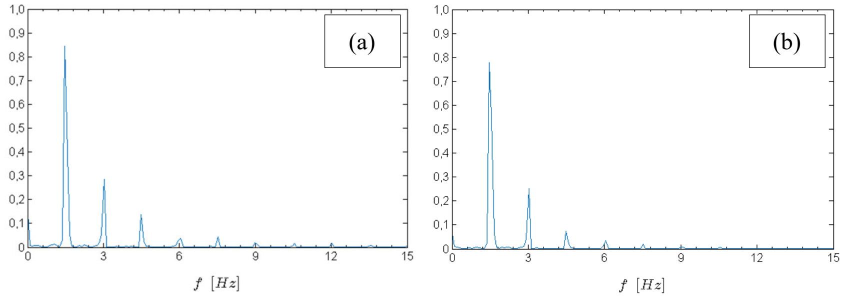

Fig. 5. (a) FFT Photometric system, (b) FFT Ultrasonic system

The ultrasonic system uses an average of measurements on a circular area on the surface of the roll wave; the laser measurement system uses a considerably smaller area (punctual) on the surface of the wave, it also takes into account the entire volume of the fluid in flow. This way, the ultrasonic system faces difficulties in changing the inclination of the surface of the roll wave at the start of the shock (the lower part of the wave). The laser measurement faces trouble on the crest of the wave, due to the change of inclination and the point of greatest volume (higher level).

4. Conclusions

When comparing the 2 methods of measurement (ultrasonic and photometric systems), one can infer that both present good results, especially considering the complexity of the phenomenon and the presence of steep fronts (waves shaped as sawtooth). Regarding the punctual values for the data series, the ultrasonic system presented 8.15% average deviation in relation to the laser system. Regarding amplitude (peak to peak), the difference was less than 1%.

About the "lost signal", the laser system presents greater susceptibility than the ultrasonic system due to measurement method, as explained in the text. Furthermore, it is noteworthy that both the experimental apparatus and the methods of both sensors and measurement techniques offer low cost of implementation, good interactivity with the experimenter and consistent results. Therefore, it constitutes in an efficient and viable option for a future monitoring system of the phenomenon and may be implemented in areas of slopes, drainage channels, avalanches corridors and torrential lava. The ultrasonic system, in this case, has large advantage in relation to the difficulty of laser for such environments. Finally, it is worth mentioning that the technique of ultrasound has been confronted with 1D mathematical model showing errors of 2 to 10% according to [21].

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