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Finite difference time domain modelling of sound scattering by the dynamically rough surface of a turbulent open channel flow

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ABSTRACT

The problem of scattering of airborne sound by a dynamically rough surface of a turbulent, open channel flow is poorly understood. In this work, a laser-induced fluorescence (LIF) technique is used to capture accurately a representative number of the instantaneous elevations of the dynamically rough surface of 6 turbulent, subcritical flows in a rectangular flume with Reynolds numbers of $10,800 \leqslant Re \leqslant 47,300$ and Froude numbers of $0.36 \leqslant Fr \leqslant 0.69$. The surface elevation data were then used in a finite difference time domain (FDTD) model to predict the directivity pattern of the airborne sound pressure scattered by the dynamically rough flow surface. The predictions obtained with the FDTD model were compared against the sound pressure data measured in the flume and against that obtained with the Kirchhoff approximation. It is shown that the FDTD model agrees with the measured data within 22.3%. The agreement between the FDTD model and stationary phase approximation based on Kirchhoff integral is within 3%. The novelty of this work is in the direct use of the LIF data and FDTD model to predict the directivity pattern of the airborne sound pressure scattered by the flow surface. This work is aimed to inform the design of acoustic instrumentation for non-invasive measurements of hydraulic processes in rivers and in partially filled pipes.

1. Introduction

Turbulent, depth-limited flows such as those in natural rivers and urban drainage systems always have patterns of waves on the air/water boundary which carry information about the mean flow velocity, depth, turbulent mixing and energy losses within that flow. Monitoring of these flows is vital to predict accurately the timing and extend of floods, manage natural water resources, operate efficiently and safely waste water processing plants and manage underground sewer networks.

Given the importance of these types of flows, it is surprising that there are no reliable methods or instruments to measure the shallow water flow characteristics in the laboratory or in the field remotely. The majority of existing instrumentation for flow measurements needs to be submerged under water and provides only local and often inaccurate information on the true flow characteristics such as the flow velocity and depth [1]. The submerged instrumentation is often unable to operate continuously over a long period of time because it is prone to damage by flowing debris and its battery life is limited. Currently, it is impossible to measure remotely and in-situ the flow mixing ability, turbulence kinetic energy, Reynolds stress, sediment erosion rates and the volume fraction of suspended/transported sediment. These characteristics are essential to calibrate accurately the existing and new computational fluid dynamics models, implement efficient real time control algorithms, forecast flooding and to estimate the potential impact of climate change on water infrastructure and the environment. Equally, there are no reliable and inexpensive laboratory methods to measure a flow over a representatively large area of a flume or partially filled pipe so that spatial and temporal flow characteristics predicted by a model can be carefully validated. The widely used particle image velocimetry [2] or LiDAR methods are notoriously expensive and difficult to set up, calibrate and make work to cover a representative area of flow either in the laboratory [3] or in the field [4].

In this sense, accurate data on the flow surface pattern characteristics are important. Recent work [5,6] suggests that there is a clear link between the statistical and spectral characteristics of the dynamic pattern of the free flow surface and characteristics of the underlying hydraulic processes in the flow. More specifically, the work by Horoshenkov et al. [5] showed that the mean

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roughness height, characteristic spatial period and correlation length are related to the mean flow depth, velocity and hydraulic roughness coefficient. The work by Nichols [6] showed that the characteristic spatial period of the dynamic surface roughness is related to the scale of the turbulence structures which cause the surface to appear rough.

In this sense the use of airborne acoustic waves to interrogate the flow surface to determine some of the key characteristics of the dynamic surface roughness is attractive to measure the in-flow processes remotely. Radio (e.g. [7]) and underwater acoustic waves (e.g. [8]) have been used extensively since the last century to measure the statistical and spectral characteristics of the sea and ocean waves. Doppler radar methods were used to estimate the velocity of rivers (e.g. [9]). However, these methods have not been used widely to measure the roughness in rivers and other open channel flows, which is surprising given the importance of a good understanding of the behaviour of these types of natural hydraulic environments. In this respect, the development of non-invasive instrumentation for the characterisation of open channel flows is impeded by the lack of understanding of the roughness patterns which develop on the surface of these types of flows and ability to model the wave scattering by these surface roughness patterns. Therefore, the purpose of this paper is to study the application of the FDTD technique to predict the time-dependent acoustic wave scattering patterns, and their directivity, which are observed above the dynamically rough surface of a turbulent, shallow water flow.

The paper is organised in the following manner. Section 2 presents the experimental facility which was used to measure the acoustic scattering patterns for a range of hydraulic flow conditions. Section 3 presents the modelling methodologies. The results and discussion are presented in Section 4.

2. Experimental method and data pre-processing

2.1. Flow conditions

For this work, the rough surfaces to be used for validating the acoustic models were generated by a turbulent flow. The hydraulic conditions studied in this work were designed to generate a number of different dynamic water surface patterns for a number of flow conditions as detailed in Table 1. Experiments were carried out in a 12.6 m long, 0.459 m wide sloping rectangular flume (see Fig. 1) which is available in the University of Bradford. The flume had a bed of hexagonally packed spheres with a diameter of 25 mm, and was tilted to a slope of $S_0 = 0.004$.

The depth of the flow was controlled with an adjustable gate at the downstream end of the flume to ensure uniform flow conditions throughout the measurement section. The uniform flow depth relative to the bed was measured with point gauges that were accurate to the nearest 0.5 mm (between 0.6% and 1.2% of the flow depths used). This was conducted at 4 positions, situated 4.4–10.4 m from the upstream flume end in 2 m increments, with uniform flow being confirmed when the values agreed to within 0.5 mm of each other. This meant that the flow was not spatially changing, i.e. no net acceleration or deceleration across the measurement frame, so that the statistical properties of the free surface roughness were uniform across the measurement area.

Table 1
Measured hydraulic conditions.

Flow condition	Bed slope S	Depth D (mm)	Flow rate Q (l/s)	Velocity U (m/s)	Reynolds number Re
1	0.004	40	5.0	0.28	10,800
2	0.004	50	8.5	0.36	15,100
3	0.004	60	12.0	0.43	24,500
4	0.004	70	16.0	0.50	32,700
5	0.004	80	21.0	0.57	38,800
6	0.004	90	27.0	0.65	47,300

The uniform flow depth, D, was varied from 40 mm to 90 mm by adjusting the flow rate using a control valve in the supply pipe, and a downstream gate was to ensure uniform flow. The flow rate, Q, was measured via a calibrated orifice plate, and varied from 5 l/s to 27 l/s. The resulting mean flow velocity, U, varied from 0.28 m/s to 0.65 m/s. The Froude number for these flows ranged from 0.36 to 0.69, such that all flows were subcritical, and Reynolds number ranged from 10,800 to 47,300 so that all flows can be considered turbulent. Table 1 presents a summary of the hydraulic conditions realised in the reported experiments. A photograph of an example of the flow surface roughness observed in flow condition 1 is shown in Fig. 2.

2.2. Free-surface position measurement

A laser induced fluorescence (LIF) technique was employed to measure the free-surface position in a vertical plane along the centreline of the flume at the test section. A diagram of the LIF arrangement for the flow surface measurement is shown in Fig. 3. A sheet of laser light was projected vertically through the flow surface, and a high-resolution camera was used to image the intersection between the laser sheet and the water surface.

An optical system was used to form and focus the laser light sheet, which illuminated a volume approximately 250 mm long in the streamwise direction and approximately 3 mm thick in the lateral direction. In order to define the free-surface clearly in the images, Rhodamine B dye was added to the flow. When illuminated with 532 nm laser light, the Rhodamine is excited, and emits light at around 595 nm. A high-pass filter lens with a cut-off wavelength of 545 nm was used to discard the ambient green (532 nm) light, but allow through the red (595 nm) light emitted by the rhodamine in the water.

The camera was installed at an elevated position, looking down towards the water surface at an angle of 15° (see Fig. 3). This setup allowed for a clear line-of-sight between the surface profile and the camera, with no opportunity for higher water surface features in front of the laser plane to obstruct the view. The camera was calibrated by capturing images of a grid of dots placed in the same plane as the laser. This enabled a direct linear transform to be calculated so that the true position of each image pixel could be determined. This enabled the position of the air–water interface to be detected for each of the 1600 columns of pixels in the recorded images. Images were captured at a fixed frequency of 26.9 Hz. For each flow condition, images were recorded for 5 min, generating a time series of 8070 images.

The images from the LIF camera were used to determine the position of the free surface from each image by detecting the threshold between the illuminated flow and non-illuminated air for each column of pixels. Fig. 4 shows the following analysis steps applied to one instantaneous image from flow condition 4. Firstly, a raw image was loaded (Fig. 4(a)). Secondly, the image pixels were binarized by setting a threshold illumination value above which a pixel was defined as fluorescing water, and below which a pixel was defined as non-fluorescing air (Fig. 4(b)). The quality of the output data was found sensitive to this threshold and so it was determined manually for each flow condition to ensure that the binarized images closely matched the raw images. Thirdly, a 5×5 two-dimensional median filter was applied to remove spurious points of brightness within the air phase or points of darkness in the water phase (Fig. 4(c)). This replaced each value with the median value of the 5×5 grid of logical values surrounding it. Each pixel column was then analysed to determine the pixel location at