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Measuring wave impact induced pressures with a pressure mapping system

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ABSTRACT

The use of a pressure mapping system for measuring wave impact induced pressures is evaluated in this paper. A set-up and a calibration methodology are suggested and employed for this work. The system is validated against pressure transducer and load cell measurements and for a range of waves breaking on a vertical seawall. For a large number (120 measurements for each case considered) of breaking and broken waves interacting with the wall, the peak pressure (P_{peak}) profiles and the pressure distribution maps reported by the system agree well with results acquired using pressure transducers. Although the pressure mapping system tends to underestimate P_{peak}, differences on the mean of the 3, 5 and 10 highest P_{peak} range within $\pm 10\%$, while for the majority of the measurements the error on the integral of the acting pressures (the acting force compared with the force measured by the load cell) ranges within $\pm 20\%$. It is concluded, that through careful calibration and set-up the pressure mapping system has the capacity to provide pressure distribution maps with a good accuracy. It is not, however, considered to constitute the absolute alternative to pressure transducers and thus a combined use is suggested for applications where a very high level of accuracy is required.

1. Introduction

As knowledge on the mechanics involved in the breaking wave-structure interaction is limited impact induced pressure measurements are one of the most important outcomes expected from hydraulic model tests. Pressure measurements are usually preferred over load measurements as they allow for the detection of vulnerable areas on the structure, while the acquisition of global loads requires at times complicated and expensive experimental layouts, especially in large scale facilities. For most physical model tests involving, e.g., coastal structures an array of pressure transducers is placed vertically at the seaward face of the structure and the data collected are used for the construction of pressure profiles and the calculation wave induced loads and moments (Cuomo et al., 2010).

Nonetheless, pressure transducers provide single point measurements and in most cases a relatively small number of transducers are used. In the same time, the high spatial and temporal variability of wave impact induced pressures (Hattori et al., 1994; Peregrine, 2003; Saruwatari et al., 2009), the limited information available even on the coherence pressure profiles (Hull and Müller, 2002), and the increased complexity on the geometry of the structures (for example, wave recurves, wave energy converters and ships) tested, drive the need for experimental measurements with a high spatial resolution.

Additional challenges emerge when cylinders and structures with more complex geometrical shapes are considered. For example, investigating the survivability of wave energy converters, offshore oil platforms or wave recurves requires detailed knowledge of the impact induced pressure distribution. However, due to technical and financial restrictions high resolution pressure maps cannot be produced using pressure transducers.

A pressure mapping system with the potential to provide pressure measurements with a high spatial resolution is described in Section 2. The system has been used in and validated for, e.g., biomedical and geotechnical applications but never before for measuring wave induced impact pressures. Nevertheless, the existing literature suggests that the accuracy of the system depends strongly on the experimental set-up and the calibration methodology employed (Baer et al., 2004; Brimacombe et al., 2009). Therefore a calibration set-up and methodology designed for application in hydraulic model tests with waves breaking on a rigid structure are proposed. The performance of the system is evaluated against pressure transducer and load cell measurements for a

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wide range of breaking conditions on a vertical seawall model in Section 3 and the work is concluded in Section 4.

2. Methodology

2.1. Experimental equipment

2.1.1. Pressure mapping system

The high speed Tekscan Pressure Mapping System (PMS) is used here. The system consists of a tactile pressure sensor (sometime referred to as pressure pad or simply pad), a connection handle and a hub allowing the simultaneous use of more than one handles and triggering from an external signal. The hub is connected to the USB port of any PC equipped with I-Scan software provided by the manufacturer along with the PMS.

A variety of tactile pressure sensors is available with their characteristics ranging in terms of number of measuring points (most commonly referred to as sensels), physical size and maximum sampling frequency. For all tests presented here the tactile sensor with model number 9500 was used. The sensor has 196 sensels spread at equal distances over a square area of 7.1 × 7.1 cm and it allows for a maximum sampling frequency of 4 kHz with and 8 bit resolution. At this point it should be highlighted that each sensel consists of an active and a 'dead' area with the latter surrounding the former. An intrinsic disadvantage is thus entailed, since the pressure is calculated as force over the full (active and 'dead') area of each sense. The pressure mapping system is not provided already calibrated by the manufacturer and its calibration prior to any test is recommended.

The calibration rig developed specifically for this work is presented in Fig. 1. The Tekscan sensor is firmly fixed below a tube (not shown in Fig. 1), on a 3 mm thick aluminum plate. As the sensor is not waterproof adequate protection from water is provided by placing the sensor in a vacuum bag (Minimatic bag 0.05 mm) and a secondary protection layer is created using a transparent, deformable/compliant foil (vacuum film NBF-740-LFT 0.05 mm). A vacuum pump is used to reassure that air is not trapped in the tactile sensor and between the sensor and the protection layers, and the vacuum pressure acting on the sensor is removed from the measurements during the post-processing. If not properly removed, entrapped air can significantly deteriorate the accuracy of system (see Tekscan, 2008; Ramachandran et al., 2013). Nevertheless, Ramachandran et al. (2013) has shown that once the formation of unwanted air pockets is prevented the response of the sensor remains the same for different vacuum levels but for all measurements presented here a constant vacuum of 40 kPa was maintained. This was indicated in preliminary tests to be the minimum vacuum required to remove all air and generate a homogenous pressure field on the sensor. It is noteworthy, that the vacuum pump was found to introduce a high frequency (25 Hz) noise to the signal but a low pass filter was also found to be very effective on removing it.

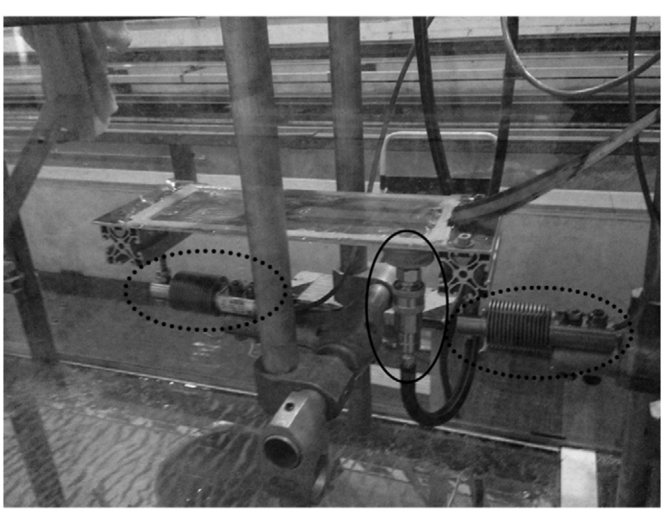

Fig. 1. Photograph of the proposed calibration rig showing the vacuum valve (solid circle), the tactile sensor, and the two load cells (dashed circles).

Impinging water-jets are used to induce dynamic pressures on the sensels of the tactile pressure sensor. The pressure pulses generated by impinging water jets resemble very closely those expected in experiments with waves breaking on rigid structures (see for example Figs. 9 and 10). During the first moments of the impact a sharp increase from 0 to peak pressure occurs and subsequently the pressure decreases as the phenomenon transcends from a dynamic to a quasi-static phase.

The impact induced load is measured using a pair of HBM Z6FC3 bending beam load cells arranged in series, (Fig. 1) but for each impact the area (A) is simultaneously measured by the Teskan sensor, (Fig. 2 on the left). Accordingly, the mean pressure (P_{LC}) acting on the sensor is calculated as the ratio of the force recorded by the load cells over the area measured by the tactile pressure sensor (Eqs. (1) & (2)).

$$A = N * A_{sensel} \tag{1}$$

where,

- N: is the number of active sensels
- A_{sensel}: is the sensel area, equal to 26 mm^2

and is used to calculate the mean pressure from the load cell measurement, as:

$$P_{LC} = \frac{F_{PLC}}{A} \tag{2}$$

where,

- F_{PLC}: is the peak force measured by the load cell
- P_{LC}: is the mean pressure acting on the tactile sensor at the time F_{PLC} occurs.

The digital output of a sensel is the considered equal to the calculated pressure multiplied by a weighting factor, Eqs. (3) & (4).

$$C_{i,j} = 1 - \frac{\overline{DO} - DO_{i,j}}{\overline{DO}} \tag{3}$$

where,

- $C_{i,j}$: is the contribution factor for a sensel with horizontal (x) and vertical (y) coordinates i, j, respectively. With $i = 1\ldots14$ and $j = 1\ldots14$.
- $DO_{i,j}$: is the digital output of a sensel with horizontal (x) and vertical (y) coordinates i, j.
- $\overline{DO}$: is the mean of the digital output of all sensels active at the time instant that the peak force was recorded by the load cells.

The combination of Eqs. (1) to (3) gives the weighted pressure, $P_{i,j}$, acting on the (i, j) sensel:

$$P_{i,j} = C_{i,j} * P_{LC} \tag{4}$$

For this work, the sensor was calibrated using 300 water jet impacts and the digital output of a sensel is plotted as a function of $P_{i,j}$ (Fig. 2 on the right). The lines plotted correspond to a linear (dashed), a power law (solid) and a 2nd order polynomial fit (dotted), and represent three different calibration algorithms. When the integral of the pressures acting on each sensel was compared with the load cell measurements statistically indistinguishable results were found for all algorithms (Table 1).

Nevertheless, the manufacturer recommends the use of a non-linear power law algorithm which was also preferred for this work (Tekscan, 2008).