



WAVE EFFECTS ON A PRESSURE SENSOR

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SYNOPSIS : Wave flume experiments indicated that for waves propagating on quiescent waters the sensor's performance improved (i.e., the difference $\overline{\Delta p}$ between the average hydrostatic and measured pressures was small and positive) when the inlet was at the centre and flush with a large, thin, smooth circular horizontal end-plate. In this case, isolation of the pressure inlet from the separated flow and vortices shed by the sensor housing was partly responsible for the observed improvement. Another reason for improvement seems to have been a much reduced value of the wave-induced oscillatory boundary layer flow, in the vicinity of the pressure inlet, as compared to the mainstream oscillatory flow. The sensor's performance was better for the case of waves riding on currents as the $\overline{\Delta p}$ in this case was the sum of a positive $\overline{\Delta p}$ for currents alone and a negative $\overline{\Delta p}$ for waves alone. This result is of special significance to tidal measurements of coastal waters in which waves propagate on tidal currents.

INTRODUCTION

Pressure sensors tend to be influenced by the dynamic nature of the measurement site such as flows, waves and suspended sediments (Joseph et al. 1993). The influence of water flow on the measurement accuracy of pressure sensors, and some design solutions to improve their performance in a flow field have been reported by Joseph et al. (1996). In this paper the experimental performance of a pressure sensor deployed in a wave field, and combinations of flows and waves is examined. Some design solutions to improve their performance in such fields have also been investigated together with justification based on principles of fluid dynamics.

RESPONSE OF A PRESSURE SENSOR TO SHALLOW WATER WAVES

When a pressure sensor is used for measurement of sea level, the sensor output is always averaged over some time-span, so that the resulting sea level signal is free from short period gravity wave fluctuations. Based on Stoke's second-order theory for progressive gravity waves, it can be shown that the measured time-averaged reduction in pressure during the measurement interval, compared to the hydrostatic pressure, is given by (Joseph et al. 1996):

$$\overline{\Delta P} = \rho g \left(C_3 - \left(\frac{C_1 T}{2\pi\tau} \right) \sin(2\pi\tau/T) - \left(\frac{C_2 T}{4\pi\tau} \right) \sin(4\pi\tau/T) \right) \quad (1)$$

where T is the wave period, and C_1, C_2, C_3 are given by:

$$C_1 = \left(\frac{H}{2} \right) \operatorname{sech}(kd) \cosh[k(d-y)]$$

$$C_2 = \left(\frac{3kH^2}{8} \right) \operatorname{cosech}(2kd) \left[\frac{\cosh[2k(d-y)]}{\sinh^2(kd)} - \frac{1}{3} \right]$$

$$C_3 = \left(\frac{kH^2}{8} \right) \operatorname{cosech}(2kd) \cosh[2k(d-y)]$$

In the above equations $k, d,$ and y correspond to wave number, depth of the sea floor, and depth of the pressure inlet below the mean water level respectively. When $\tau = nT$, where n is an integer, equation (1) becomes:

$$\overline{\Delta P} = \rho g C_3 \quad (2)$$

Thus, even if averaging over full periods is performed, the term C_3 , being a non-periodic constant, will provide a non-zero value for $\overline{\Delta P}$. Besides this, the real ocean consists of several wave constituents of differing heights and periods which cannot be averaged out by the choice of a single value of τ . It is, therefore, evident that averaging over a very long time does not remove the wave-induced error in the measurement of pressure.

Equation (1) provides predicted error estimates in the measurement of pressure using a transducer whose pressure inlet is exposed to an undisturbed progressive gravity wave-field propagating in shallow waters. Figs.1(a,b) are based on the above estimates and with the shallow water wave sustainability criterion, show the dependence of $\overline{\Delta P}$ on wave periods (T) and wave heights (H) for a typical low- and high-tide situations respectively. It is seen that the dependence of $\overline{\Delta P}$ on H is significantly stronger than on T . These results also indicate that $\overline{\Delta P}$ is almost constant for long-period waves, but decreases non-linearly with decreasing wave period. A practical method of reducing wave-induced errors would be to optimise the geometry of the pressure intake mechanism.

EXPERIMENTS AND RESULTS

Details of the pressure sensor and the data logger used in the present experiments have been described by Joseph et al. (1995).

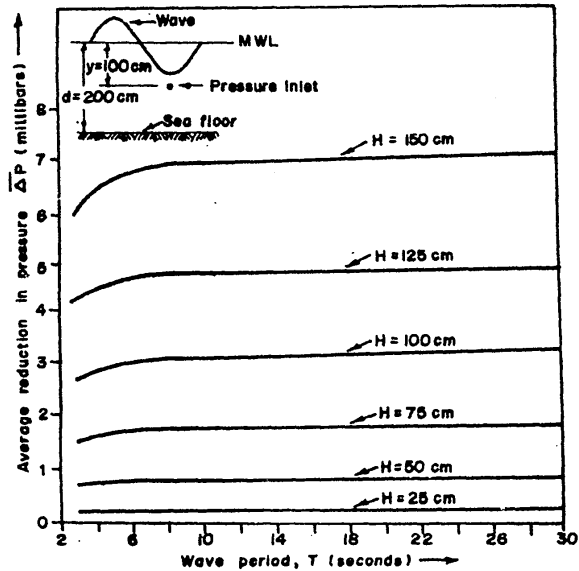


Fig.1(a). Predicted dependence of average pressure reduction ΔP on wave period, in shallow waters, for indicated wave heights for a typical low-tide situation (averaging carried out over full wave period or its multiples).

The pressure sensor with its housing was rigidly mounted on a support mechanism which could be rotated through 360° about the axis of the support rod, permitting studies of the horizontal azimuthal response of the sensor with changing wave directions. A wave flume having a plunge type wave-maker at the Institute of Oceanographic Sciences, U.K was used for the experiments.

Schematic diagrams of differing hydro-mechanical front-ends of the sensor are given in Fig.2. The configuration of the pressure intake mechanism for the first set of experiments was somewhat similar to many conventional settings where the pressure inlet protruded into the wave field. The protruding stainless steel tube, of length 2.5 cm, was filled with silicone oil to prevent trapping of air inside the pressure inlet. Experiments were conducted with the averaging time set to 28.125 second, for differing wave heights and a constant wave period of 2 seconds, the latter being the maximum wave period that the wave-maker was capable of generating. Subsequent experiments were conducted without the protrusion. As stand-offs alter the dynamics of the fluid surrounding them, the azimuthal response of the sensor was also investigated. Pressure variation as a function of H for different configurations are shown in Fig.3. Addition of a parallel plate of diameter D reduced the value of ΔP for most of the azimuthal

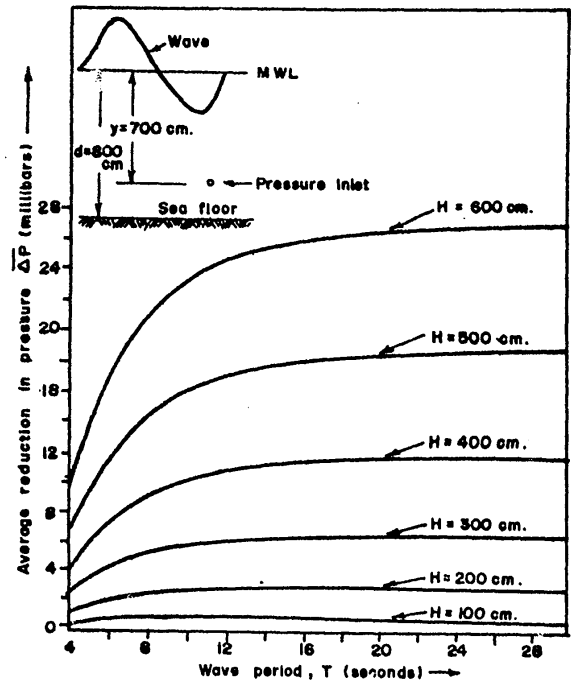


Fig.1(b). Predicted dependence of average pressure reduction ΔP on wave period, in shallow waters; for indicated wave heights for a typical high-tide situation (averaging carried out over full wave period or its multiples).

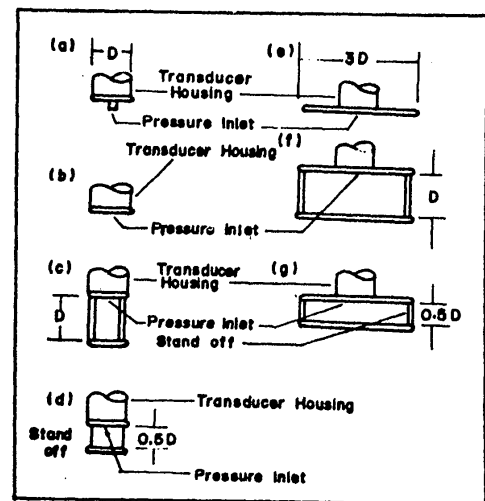


Fig.2. Differing hydromechanical front-ends at the inlet of pressure sensor.

directions, even being negative in some directions. Locating the pressure inlet at the centre of a larger horizontal circular plate of diameter $3D$ gave rise to a significant improvement in the performance of the sensor compared to all other hydro-mechanical front-end designs. However, use of a large parallel plate of diameter $3D$ gave rise to deteriorating effects on the performance of the sensor.

In coastal waters the waves, in general, propagate on currents rather than on quiescent waters. Current-induced modifications of waves affect the pressure field accompanying the wave. Results

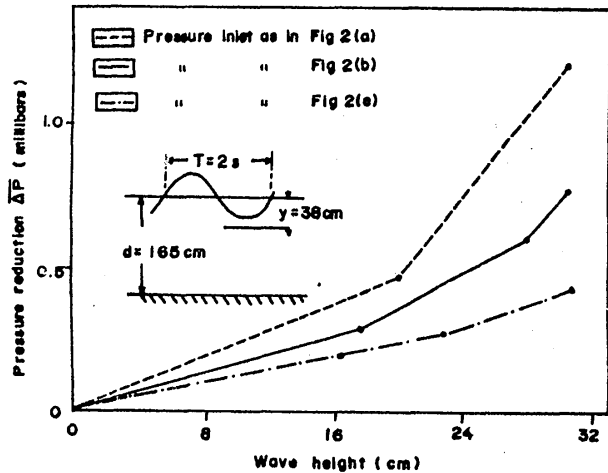


Fig. 3(a). Response of a pressure sensor for hydromechanical front-ends of Fig. 2(a, b, e) to progressive gravity waves propagating on quiescent water.

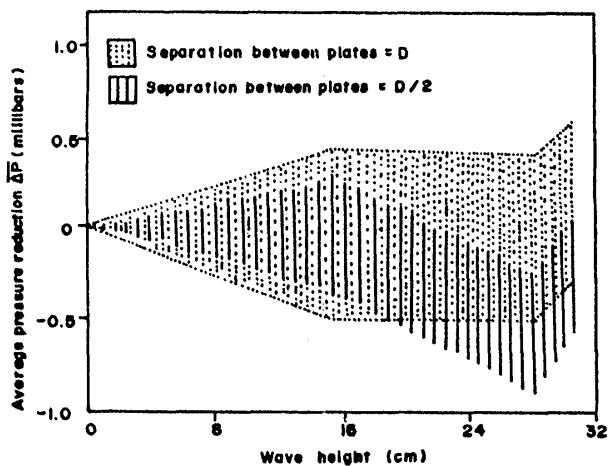


Fig. 3(b). Spread in horizontal azimuthal response of a pressure sensor for small parallel plates of Figs. 2(c, d) for progressive gravity waves propagating on quiescent water.

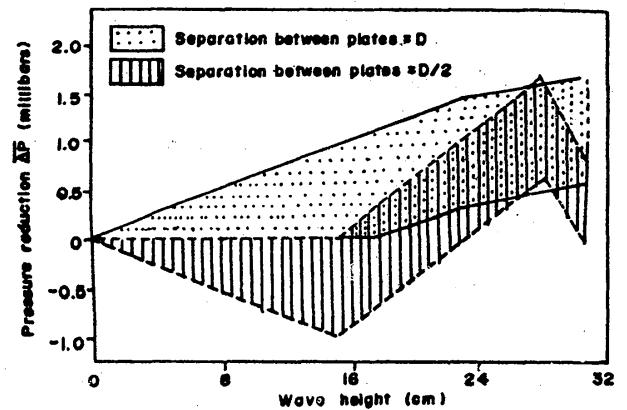


Fig. 3(c). Spread in horizontal azimuthal response of a pressure sensor for large parallel plates of Figs. 2(f, g) for progressive gravity waves propagating on quiescent water.

of the experiments, with waves riding on positive and negative currents, are shown in Fig. 4. Use of a horizontal thin circular end-plate of diameter $3D$ yielded a very significant improvement in the performance of the sensor. Addition of a second identical plate separated from the first by a distance equal to D yielded a further improved performance at larger wave heights.

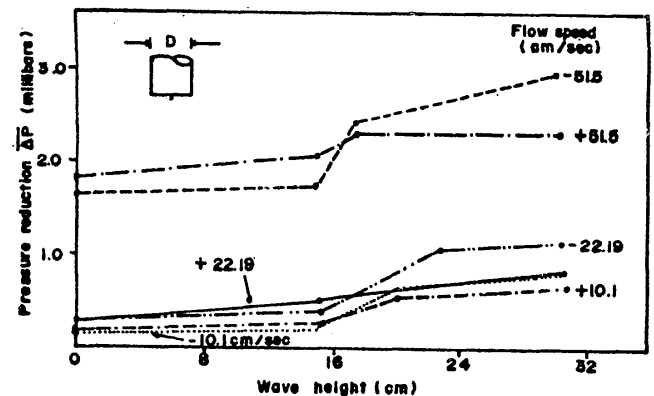


Fig. 4(a). Response of a pressure sensor with a protruding inlet as in Fig. 2(a) for waves riding on positive and negative currents.

DISCUSSION OF RESULTS

From boundary layer theory, the velocity u within the laminar boundary layer of a flat plate is given as (Teleki, 1972):

$$u(y_b, t) = U_\infty [\cos(\omega t) - \exp(-\eta) \cos(\omega t - \eta)] \quad (3)$$

where U_∞ is the amplitude of the mainstream oscillatory flow,

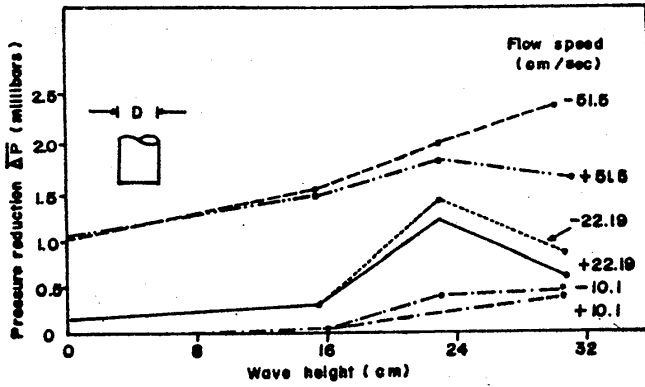


Fig. 4(b). Response of a pressure sensor for pressure inlet located at the centre of the end-plate of the sensor housing and flush with the plate surface as in Fig. 2(b) for waves propagating on positive and negative currents.

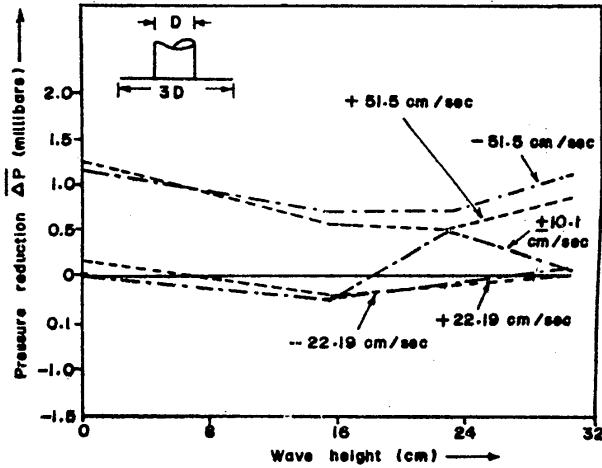


Fig. 4(c). Response of a pressure sensor for pressure inlet located at the centre of a large end-plate as in Fig. 2(e) for waves propagating on positive and negative currents.

and

$$\eta = y_b \sqrt{\frac{\omega}{2\nu}} \quad (4)$$

In this relation y_b , ω and ν are respectively the distance normal to the plate, the radian frequency of the wave, and kinematic viscosity of the fluid. U_∞ is given by the relation:

$$U_\infty = \left[\frac{(\omega)}{\sinh(kd)} \cosh[k(d-y)] \right] \quad (5)$$

Based on the expressions (3), (4) and (5), distribution of the root-mean-square flow velocities in the vicinity of the pressure inlet may be computed. Since the value of $\overline{\Delta P}$ is a function of

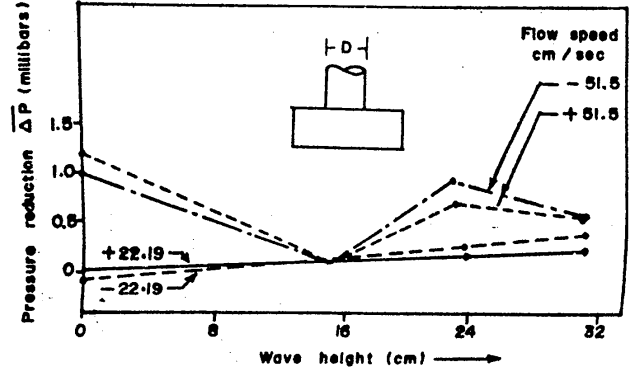


Fig. 4(d). Response of a pressure transducer when its pressure inlet is attached to large parallel plates as in Fig. 2(f) for waves propagating on positive and negative currents.

$\overline{u^2}$ it is necessary to evaluate the latter as follows:

$$\overline{u^2(y_b)} = \frac{1}{\tau} \int_0^\tau u^2(y_b, t) dt \quad (6)$$

It can be shown that:

$$\overline{u^2(y_b)} = (A - B - C + D) \quad (7)$$

where A, B, C, and D are as follows:

$$A = \left(\frac{U_\infty^2}{2} \right) + \left(\frac{U_\infty^2}{4\omega\tau} \right) \sin(2\omega\tau)$$

$$B = \left(\frac{U_\infty^2 \exp(-\eta)}{2\omega\tau} \right) [\sin(2\omega\tau - \eta) + \sin(\eta)]$$

$$C = U_\infty^2 \cos(\eta) \exp(-\eta) + \frac{U_\infty^2}{2} \exp(-2\eta)$$

$$D = \left(\frac{U_\infty^2 \exp(-2\eta)}{4\omega\tau} \right) [\sin(2(\omega\tau - \eta)) + \sin(2\eta)]$$

In the above expression, η and U_∞ are given by relations (4) and (5) respectively. Fig. 5 shows the root-mean-square flow velocities [i.e. $\sqrt{\overline{u^2(y_b)}}$], near the pressure inlet, within the boundary layer of the flat end-plate and for differing experimental wave heights. The corresponding $\overline{\Delta P}$ values are shown in Fig. 6. The values of $\overline{\Delta P}$ have been estimated using Bernoulli's equation. The protruding pressure inlet exhibited large $\overline{\Delta P}$ values because the inlet was beyond the laminar boundary layer of the plate, given by (Kundu, 1990):

$$\delta \approx 4\sqrt{\frac{\nu}{\omega}} \quad (8)$$

The smaller $\overline{\Delta P}$ values obtained when the pressure inlet remained flush with the end-plate of the sensor's housing can be attributed to a retarded flow very near to the pressure inlet. The improved performance associated with the use of a thin plate of diameter $3D$ appears to be due to isolation of the pressure inlet from the disturbed flow in the vicinity of the sensor housing.

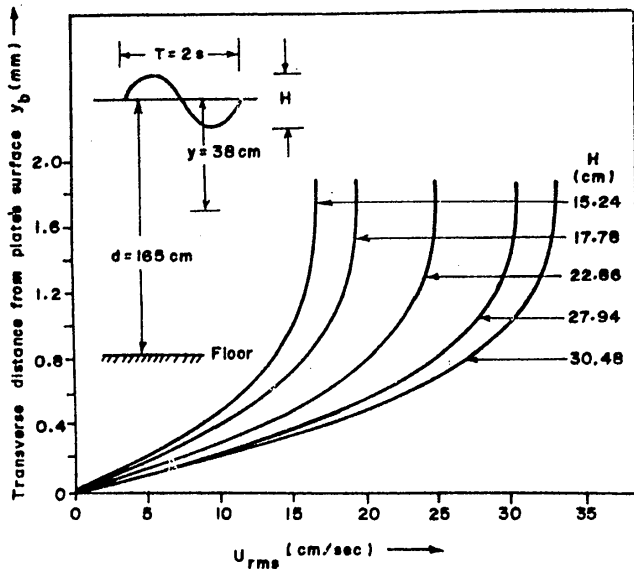


Fig.5. Root-mean-square flow velocity u_{rms} as a function of y_b within the laminar boundary layer for differing experimental wave heights.

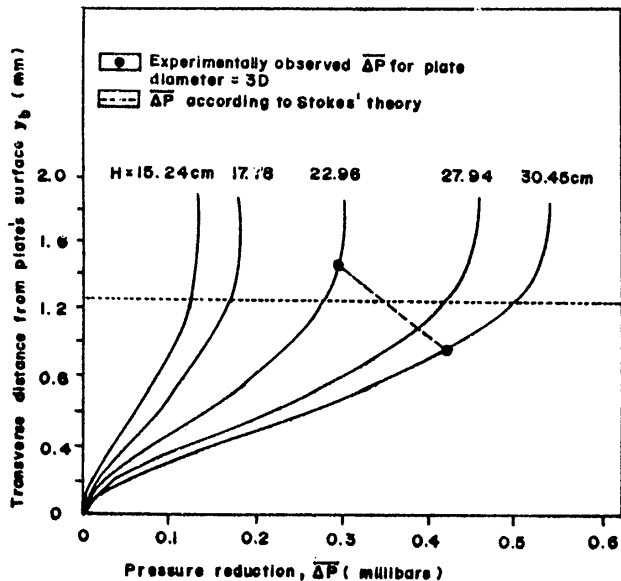


Fig.6. Variation of ΔP as a function of y_b for differing wave heights.

An important role of horizontal parallel plates was to modify the wave-induced elliptical motions of water in the vicinity of the pressure inlet. For all the experimental wave heights, the vertical heights ($2B$) of the minor axes of these ellipses were greater than the vertical separation between the horizontal plates in the case of plate separation equal to $0.5 D$ ($D=12.8$ cm). For most of the wave heights, the distance $2B$ was greater than D . Thus,

deformations of the orbital path or generation of smaller secondary orbital motions (lower $2B$ values) must have given rise to unequal momentum distributions in the horizontal and the vertical directions, and resulted in the observed enhancement. This effect is expected to be more predominant in a field situation where wave heights are usually much larger than the present experimental values. In the case of waves propagating on currents, interactions or any kind of resonant coupling between these secondary orbital motions and the vortices shed from the stand-offs at the Strouhal frequency may have resulted in radiation stress variations which contributed to the observed reduced values.

CONCLUSIONS

A protruding pressure inlet on a pressure sensor is most susceptible to wave-induced errors. The sensor's performance in a wave field can be significantly improved by locating the inlet at the centre of a thin horizontal circular plate whose diameter is $3D$ or more. In the case of combination of flows and waves the sensor's performance can be enhanced by protecting its inlet with a pair of large thin parallel plates separated by a distance equal to D .

ACKNOWLEDGEMENTS

The authors are grateful to Joe Rae and his colleagues of the Technology Group of Proudman Oceanographic Laboratory, U.K for all the help in carrying out these experiments. The present work was funded in part by the British Council through the Technical Co-operation Training Award to Antony Joseph. Antony Joseph is thankful to B.N. Krishnamurthy, Director, DOD and to Caroline Marriot, British Council, Manchester for their help in many ways.

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