6.1 The present work

In the present study, the response of a pressure transducer to laminar and turbulent flows; waves and combination of flows and waves; and suspended sediments have been investigated. Based on studies using differing front-end configurations, an optimum front-end design for a natural environment has been achieved. Further, a method has been identified and tested to measure in-situ effective density of natural water. This method could also automatically compensate for fluid density variations arising from various sources such as salinity and temperature variations of natural waters with changing seasons and phases of tide, or as a result of the presence of suspended sediments. The overall performance enhancement achieved with the use of differing techniques are summarized below.

6.1.1 Response to flows

Flow channel experiments have been conducted on a pressure transducer with differing configurations of hydro-mechanical front-ends for laminar and turbulent flows. The study showed that a protruding pressure inlet is most susceptible to flow-induced average reduction $\Delta P$ in the measurement of pressure compared to hydrostatic pressure at the same depth. This appears to be due to the fact that the pressure inlet protruded beyond the boundary layer, and was exposed to the
separated flows and vortices shed from the transducer housing and nearby structures. Locating the pressure inlet at the centre of a circular end-plate provided some improvement (i.e., a smaller value of $\Delta P$) in the transducer's performance. This was likely to have been the result of the pressure inlet's proximity to the boundary layer of the flat plate, where the flow is much weaker than the mainstream flow. Reduction in the influence of flow separation effects such as vortices and turbulence must also have played a role in the observed improvement. The improvement became significant when the diameter of the thin flat plate was 3 times that of the pressure housing. In this case the improvement, for laminar flows, was $\approx 3$ times as compared to a protruding pressure inlet. An enhanced performance of the pressure transducer (0.12% of F.S compared to 0.34% in the case of a protruding pressure inlet), associated with a large thin flat plate with rounded edge, can be attributed to the isolation of the pressure inlet from the flow disturbances caused by the transducer housing and an increase in the boundary layer thickness at the centre portion of the plate. A marginal increase in the performance of the transducer by increasing the diameter of the thin plate to beyond 4 times that of the transducer housing has been shown. For laminar flow, use of a parallel end-plate assembly had a deteriorating effect on the transducer's performance.

Proximity of the transducer housing to a piling adversely affected the performance of the transducer, especially its horizontal azimuthal response. The transducer's performance could be significantly improved by placing a perforated
curved shield in front of the transducer housing at a distance of more than 15 cm. The enhancement in performance in this case was \( \approx 5 \) times as compared to that in the absence of this shield. This improvement (0.08% of F.S as compared to 0.38% in the absence of this shield) was due to the retarded velocity of the jet flows from the circular orifices of the perforated shield. A similar enhancement was achieved by locating the pressure inlet at the centre of a large diameter thin flat circular plate having a rounded edge, but this scheme suffered from a poor horizontal azimuthal response. A pair of parallel plates, separated by a distance equal to the diameter of the pressure transducer housing and of diameter 3 times that of the housing, provided a good azimuthal response of the transducer up to turbulent flow speeds of 100 cm/sec. At this speed the spread in \( \Delta P \) was < 1 mbar compared to 6.29 mbars without a plate. This was the result of the stabilising capability of the parallel plates for turbulent flows which originated from the piling. Based on flow flume investigations the following recommendations can be made:

1. For laminar flows the inlet of the pressure transducer should be at the centre and flush with a horizontal end-plate (edge rounded or chamfered) of diameter equal to 3 to 4 times that of the pressure housing.

2. For turbulent flows a pair of thin circular parallel plates (edges rounded or chamfered) of diameter 3 to 4 times that of the housing and separation equal to the housing diameter is to be preferred.
6.1.2 Response to waves and combination of waves and flows

Wave flume and tow-tank experiments have also been conducted on the pressure transducer with the previously mentioned differing configurations of hydro-mechanical-front-ends to evaluate its performance under regular progressive gravity waves and combinations of flows and waves. This study also showed that a protruding pressure inlet is most susceptible to a reduction in the measurement of pressure. An improvement observed when locating the pressure inlet at the centre of a circular horizontal end-plate is likely to have been the result of the pressure inlet's exposure to the wave-induced oscillatory boundary layer flows whose r.m.s. values are much weaker than that of the mainstream oscillatory flow. A further enhanced performance of the pressure transducer associated with the use of a large thin flat end-plate (≈ 3 times compared to a protruding pressure inlet) can be attributed to the isolation of the pressure inlet from the oscillatory flow disturbances caused by the transducer housing and from vortices.

A significant result with the use of a horizontal parallel-plate front-end in place of a single horizontal end-plate was the occurrence of negative values of \( \Delta P \) for most horizontal azimuthal directions (upto \( \approx -1 \) mbar at wave heights of \( \approx 28 \) cm). This result is probably due to the wave-induced modified elliptical motion of water particles between the plates interacting with the vortices shed by the stand-offs. Vertical elongation of elliptical orbits within the parallel plates may also have contributed to the observed negative values of \( \Delta P \).
In the case of waves propagating with and against a flow it was found that the mean reduction in pressure $\Delta P$ differed from those suggested by a linear superposition of wave and current velocities. This was especially true in the case of waves riding on negative currents. However, the experimentally observed $\Delta P$ values ($\Delta P_{\text{expt}}$) were closer to those predicted by the linear superposition of $\Delta P$ values due to waves (Stokes) and flows considered separately. The $\Delta P_{\text{expt}}$ values were also closer to the sum of $\Delta P$ calculated from the r.m.s. values of mainstream oscillatory flow and $\Delta P$ due to the steady mainstream flow. The predicted values of $\Delta P$ for wave-current interaction in Stokes' second-order theory were nearer to $\Delta P_{\text{expt}}$ for small mainstream flows with the similarity in trends being maintained over a wider range of flows.

For a parallel-plate front-end, the experimental observations of a reduced value of $\Delta P$ for combinations of waves and currents as compared to currents alone appears to be due to the fact that the observed $\Delta P$ is a sum of a positive current-induced pressure difference and a negative wave-induced $\Delta P$. Thus, for combination of waves and currents a relatively small positive $\Delta P$ (0.5 mbar, typically) was found. This implies that a horizontal parallel-plate front-end mechanism is more effective in the presence of combination of waves and flows than solely for flows or for waves.
6.1.3 Response in turbid natural waters

Pressure measurements were made in suspended-sediment-laden turbulent waters of the Hugli estuary and a partially constrained turbid water body at Bombay harbour using a single pressure transducer; and in a cove in the turbid waters of the Humber estuary, North Sea using two bubblers separated by a precisely known vertical distance. These led to the inference that the effective depth-mean in-situ density $\overline{\rho}_{eff}$ of turbid natural waters are less than their densities in a static environment. In-situ values of water density measured using conductivity and temperature data, and those of water samples measured by a hydrometer (neither of these methods account for the presence of suspended sediments) showed that the values of $\overline{\rho}_{eff}$, which contributed to the fluid pressure, were always less than the density of water free from suspended sediments.

The values of $\overline{\rho}_{eff}$ differed from one tidal cycle to another. In the Hugli estuary, the values of 0.993 g/cm$^3$ and 0.974 g/cm$^3$ observed during two tidal cycles (measured over two successive slack waters) were less than the sediment-free fluid density of 1.020 g/cm$^3$ by 2.65% and 4.51% respectively. In the turbid waters of the Bombay site, the effective density of 1.001 g/cm$^3$ (measured over two successive slack waters) was also less than the measured sediment-free water density of 1.023 g/cm$^3$ by 1.86%. Time-series measurements in the Humber estuary at a 10-minute interval indicated that the in-situ effective density had a minimum value of 1.007 g/cm$^3$ during mid-tide and thereafter gradually in-
creased to a maximum value of 1.015 gm/cm$^3$ at high tide slack water. These values were also less than the sediment-free water density of 1.019 gm/cm$^3$ by 1.18% and 0.39% at mid-tide and high-tide slack water respectively. The corresponding reduction in the effective density values compared to the bulk density of 1.035 gm/cm$^3$ were 2.71% and 1.93% respectively.

It has been found that the application of the bulk density or the sediment-free water density for conversion of measured pressure to tidal height gives rise to an under-estimation of tidal range. The under-estimation is more significant with the use of bulk density. Inter-comparison water level measurements showed that the under-estimation error can be reduced to negligible values by the use of effective density for conversion of measured pressure to water level. This shows that in-situ pressure measurements from two or more levels separated by precisely known vertical distances, followed by the application of the estimated effective density for calculation of water level can significantly improve water level measurements in turbid waters using pressure data.

There was a close agreement between the effective density of clear natural waters of Zuari estuary, estimated from pressure measurements and the density of water samples measured using a precision density meter. The observed reduced effective density of turbid natural waters therefore implies that suspended sediments play a hitherto unknown role in reducing the effective density of turbid natural waters. A close agreement of the pressure-derived water levels in turbid natural waters with those measured using a tide staff or a float-gauge when the
reduced effective density values were applied on the pressure data clearly indicates that the concept of reduced effective density is a real phenomenon with a practical consequence. A lift force exerted on the suspended particulates as a result of microturbulence in the flowing water body and/or rotation of these particulates and the trapping of microbubbles by them might be at least two causal factors for the observed reduced effective density of turbid natural waters.

Continued investigations and repeated confirmatory measurements in differing turbid natural water bodies in India and U.K by the present author and co-workers at the National Institute of Oceanography, Goa and the Proudman Oceanographic Laboratory, U.K led to the unique finding that one of the reasons for the discrepancies in water level measurement in the turbid natural waters using a pressure transducer is the result of a hitherto unknown phenomenon of reduced effective density of turbid natural waters. The measurement error is not due to instrumental error or discrepancies in measurement. The measurement error arising from this unique phenomenon can be corrected with the application of this reduced effective density on measured pressure.

6.2 Suggestions for future work

An important aspect for further study is the tilt response of a pressure transducer with differing configurations of hydro-mechanical front-ends. Such studies are necessary as these have important implications to open ocean measurements in terms of their precision and accuracy. Discussed below are several suggestions for
the enhancement of the accuracy of sea level measurements in complex estuarine and marine environments.

6.2.1 Modified bubbler design

In the U.K, bubblers attached to pneumatic tubes are extensively used in all the 42 tide stations to transfer sea water pressure to land-based gauge stations where the pressure is measured using differential Digiquartz pressure transducers. As the bubbling point is the pressure inlet, a suitable hydro-mechanical front-end attached to this bubbler would improve its performance under natural conditions where it is deployed. As reliable operation of the bubbler requires the free escape of air from its bubbling point, the use of horizontal parallel plates would not be desirable in this case. Use of a single horizontal plate with the bubbling point flush with the top face of the plate may also not be desirable due to the vulnerability of the horizontal flat plate to sediment deposition. A suitable alternative mechanism would therefore be necessary in the case of the bubblers. Based on the result of flow flume experiments in the present study with the use of a perforated protective cover on a pressure transducer as well as a consideration of static pressure probes for measurement in adverse atmospheres by Nishiyama and Bedard (1991), it appears that a perforated hemisphere [Fig. 6.1(1)] would be a suitable hydro-mechanical front-end for a bubbler. Locating the bubbling point at the centre of a perforated hemisphere would have several advantages, the most important of which is that the free escape of air bubbles is preserved.
A perforated hemisphere of suitable diameter, size of holes, and separation between neighbouring holes would keep the fluid medium within this hemisphere free from the disturbances of flows and waves as a result of the retarded jet flow action (Schlichting, 1968). Further, the hemispherical shape would improve the azimuthal and tilt responses of the bubbler. As the present studies with a perforated metal shield have indicated, the suggested perforated cover is likely to effectively take care of the adverse influences arising from separated flows and the resulting vortices which might be shed by the edges of the bubbler chamber as well as from the mechanical hardware to which the bubbler is attached. A multi-layered perforated hemisphere could also be tested in a flow flume to ascertain its effectiveness. Alternatively, the bubbler chamber and the bubbler point could also both be surrounded by a perforated sphere so that the air-water interface would also be free from flow- and wave-induced disturbances. As the bubbler chamber is usually rigidly mounted on a structure, attention need be given only to the horizontal azimuthal response. In this case, the perforated sphere may be replaced by a perforated cylinder [Fig. 6.1(2) which would be more compact than the former. In order to avoid marine growth, the perforated cover would need to be made of copper in all long-term measurements. Copper, with its toxicity to certain forms of marine life, would be expected to significantly reduce fouling during prolonged exposure in sea water (Huguenin and Ansuini, 1975).
Figure 6.1: Proposed schemes to reduce flow- and wave-effects on a pneumatic bubbler. Bubbler protected by: (1) a portion of a perforated copper sphere, (2) a perforated copper cylinder.
6.2.2 Tilt-response enhancement of a pressure transducer and miniaturisation of its front-end

A large horizontal single- or parallel-plate front-end configuration has the disadvantage of being bulky and inconvenient to handle during transportation and installation. It is likely from its very nature that tilt-response characteristics of a single- or parallel-plate front-end system will be poor beyond a certain small range of tilt angles. Studies on a single-disk probe for atmospheric pressure measurement (Sinclair, 1965) and tilt experiments on current meters (Appell, 1979; Joseph and Desa, 1994) have indicated that tilt response can be significantly different for positive and negative tilt angles of the same magnitude. Although tilt response may not be an important aspect of concern in most cases of rigidly mounted transducers, there are situations such as moored- or sea floor mounted-measurements in which poor tilt response can be a concern. In view of the advantages of a miniature front end configuration, a likely design of a perforated hydro-mechanical front-end is shown in Fig. 6.2(1). A multi-layered design [Fig. 6.2(2)] may also be evaluated under different flow and wave conditions. Positive and negative tilt response characteristics of pressure transducers attached to horizontal single- and parallel-plate front-ends, as well as the proposed front-ends need to be investigated to gain an indepth understanding of the behaviour of these differing systems. From the point of view of ease in handling, transportation and installation, as well as tilt-response characteristics, the suggested perforated front-end configuration is likely to be a useful improvement over the
Figure 6.2: Proposed schemes to reduce flow- and wave-effects on a pressure transducer. Pressure inlet protected by: (1) a single-layered perforated copper hemisphere, (2) two concentric perforated copper hemispheres.
designs used in this work. With this suggested modification, the wave-induced elliptical motions of water particles between the parallel plates of the front-end configurations used here, are unlikely to be present.

6.2.3 Design of an enhanced sea level measuring system with compensation for fluid density changes

Changes in the in-situ effective density of turbid natural waters have a direct influence on the measurement of pressure and, therefore, on the estimated water level and tidal range. It will be interesting to have a further detailed study of this hitherto unknown phenomenon. Such studies will not only result in a better understanding of the phenomenon but also result in the measurement of tide with a significantly improved precision.

The suggested technique for this purpose involves the measurement of in-situ effective depth-mean density of the fluid column over more than one depth segments. As the quiescent-state precision of a pressure transducer tends to be masked by many site-related factors, it appears that better precision in tide level measurements can be achieved by the use of more than one low-precision (low-cost) pressure transducer deployed at different depths rather than a single high-precision (high-cost) pressure transducer. Three depth segments, one below low-tide level and another two below mid-tide level (Fig. 6.3), are likely to provide an enhanced knowledge of the vertical distribution of depth-mean in-situ effective densities. As transducers (1) and (2) are located below the C.D, the in-situ depth-mean effective density $\bar{\rho}_1$ of the fluid column represented by segment 1 can be
Figure 6.3: Proposed scheme for density-compensated sea level measurement using pressure transducers.
estimated during all the phases of tide. When the water level exceeds the mid-tide level the depth-mean effective densities $\bar{\rho}_1$, $\bar{\rho}_2$, and $\bar{\rho}_3$ of fluid column segments (1), (2), and (3) respectively can be estimated. By allocating suitable threshold values for the pressure outputs $P_1$, $P_2$, and $P_3$ of the transducers (1), (2), and (3) respectively, those transducers which are fully submerged in water can be identified by the data logger. During low tide, when only transducers (1) and (2) are submerged, the estimated value of $\bar{\rho}_1$ can be applied on $P_1$ to estimate the tide level. When the water level exceeds the mid-tide level, when all the three transducers are submerged, the estimated value of $\bar{\rho}_3$ can be applied on $P_1$ to yield an optimum estimate of tide level. Since $\bar{\rho}_3$ represents the effective depth-mean density of a long segment of fluid column, the application of $\bar{\rho}_3$ is likely to provide a reasonably accurate tide level estimate even during high tide slack waters. The use of three depth segments would lead to reduction or exclusion of inherent systematic errors. Measurements of $\bar{\rho}_1$, $\bar{\rho}_2$, and $\bar{\rho}_3$ over a long period of time covering different seasons is expected to yield a much improved understanding of the dynamics involved, and their relation to sediment suspension. With the aid of suitable hydrodynamic models the suggested measurement scheme is likely to yield valuable time-series data on sediment transport.

Having gained a greater understanding of the intricacies of a pressure transducer's response under different site conditions, it would be appropriate and necessary that the benefits of these investigations are utilised to achieve the end-goal of accurate tidal measurements from clear and turbid natural waters using pres-
sure measurements. The measurement scheme shown in Fig. 6.3 has been designed to achieve this challenging goal which even an established and reliable sea level measuring instrument manufacturer (M/s. Aanderaa Instruments, Norway) avoided undertaking in the case of the Hugli estuary.

From an instrumentation point of view, the present investigations have achieved the following: Based on studies using differing front-end configurations, an optimum front-end design for a natural environment has been achieved. Further, a method has been identified and tested to measure in-situ the effective density of natural waters. The method could also automatically compensate for fluid density variations arising from various sources such as salinity and temperature variations with changing seasons and phases of tide or as a result of the presence of suspended sediments. The concept of reduced effective density may perhaps open up new vistas in the understanding of the dynamics of the unique fluid-mud phenomenon occurring in some locations of South America and the coast of South West India during some seasons.

The attitude of the philosopher has rightly been followed in the work discussed in this thesis, especially in tracing the hitherto unknown phenomenon of reduced in-situ density of turbid natural waters, based on repetitive experiments and observations by systematic variation of conditions. This concept has thrown some light on a problem which is not only important for abstract knowledge but also to understand the behaviour of a pressure transducer in a natural environment. This is echoed in Max Born’s essays on ‘Natural Philosophy of Cause and
Chance'; 'Only in physics has a systematic attempt been made to use the notions of cause and chance in a way free from contradictions. Physicists form their notions through the interpretation of experiments. This method may rightly be called Natural Philosophy'.