Wave measurement using pressure transducer

L. Cavaleri
Laboratorio per lo Studio della Dinamica delle Grandi masse, CNR, San Polo 1364, Venice, Italy.

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ABSTRACT
Routine wave measurements are often carried out by means of submerged pressure transducers. Besides notable advantages, the use of this instrument implies some problems, the most important being the bias of its output due to the dynamical effect of the relative motion of water particles. This effect is quantified, and the percentage error consequent to it is evaluated.

After a survey of the possibilities to overcome the problem, a solution is proposed in order to reduce the relative error to very limited values. The solution has been checked in a series of tests carried out in a wave tank, and the results indicate that the solution is suitable for practical use. This has been verified during extensive measurements in the open field, whose results are discussed in order to evaluate the proposed solution.


INTRODUCTION
The use of a pressure transducer for wave measurements presents notable advantages in comparison with other systems. Besides the limited cost of the instrument itself and the precision available, there are its over all sturdiness, the small dimensions and the low energy consumption. Moreover, most systems are used on the surface, whereas a pressure transducer can be placed submerged, out of the way of being easily damaged.

The underwater use does in turn carry its own problems. Fowling can be very active, to the point of biasing the results. The transducer must be firmly fixed, either on the bottom, if on a limited depth, or on a fixed structure. Finally, the critical point is the loss of information present while going down far from the sea surface, and the
The formulas most commonly used are derived from the linear theory of waves (see Kinsman, 1965, p. 134), but the experiments carried out to verify it (Draper, 1957; Tsyplyukhin, 1963; Kawanabe, Taguchi, 1968; Esteva, Harris, 1970), even if not completely consistent to each other, all together suggest that differences from the theory can be larger than 10%.

Recently (Cavaleri, Ewing, Smith, 1978), an accurate experiment was carried out on an oceanographic tower, to observe in detail, among other things, the actual attenuation of waves with depth. It was found that waves are more attenuated than it is foreseen by the linear theory, the difference being up to 10%. The factor of approximation is not constant, but it varies markedly with frequency and with the depth of the transducer.

When arguing about a few percents of difference between theory and experiments, the accuracy of the results is mandatory. While the accuracy of a pressure transducer is often sufficient for this, we found that a strong source of error was connected to the relative motion of the water respect to the transducer. This in fact does not measure just the pressure variations respect to the mean (i.e. to the undisturbed hydrostatic value), variations consequent to the wave presence (henceforth called wave pressure), but also the dynamic effect due to the relative motion of the surrounding water particles (the latter will be referred to as dynamic pressure). The difference can be positive or negative, depending on the direction of instantaneous flow with regard to the transducer itself.

This paper deals with the estimate of this error, both as absolute and relative value. An artifact devised to avoid the effect of water motion is indicated, together with the results of the tests carried out to verify its correct functioning. Finally, we present some results, obtained from actual measurements in the sea, comparing the output of the pressure transducers with the theoretical results obtained from simultaneous surface measurements.

ERROR CONSEQUENT TO WATER MOTION

In the sea, the motion of a water particle consequent to the presence of waves is tridimensional. To discuss the problem, we can simplify it referring to a monochromatic, unidirectional wave field.

To estimate the error due to the relative motion between water and transducer, we use the formulas from linear theory of waves in deep water conditions (Kinsman, 1965, p. 134 and 144):

\[ u = a \sigma e^{-kz} \cos (kx - \sigma t), \]  
\[ w = a \sigma e^{-kz} \sin (kx - \sigma t), \]  
\[ p = \gamma ae^{-kz} \cos (kz - \sigma t), \]

where \( u, w, \) horizontal, vertical components of local velocity (in the plane normal to wave crests); \( p, \) pressure consequent to wave motion; \( \gamma = \rho g, \) with \( \rho, \) water density and \( g, \) gravity acceleration; \( a, \) wave amplitude; \( \sigma, \) circular frequency \( = 2 \pi f; \) \( L, \) wave length; \( k, \) wave number \( = 2 \pi / L; \) \( z, \) vertical coordinate, positive downwards; \( x, \) horizontal coordinate; \( t, \) time.

A transducer can be thought of as an object with a face sensitive to the local pressure. While a static pressure or that due to the passage of a wave [given by (3)] acts in all the directions, hence it is felt by the transducer independently of its spatial orientation, the dynamic effect of water motion is due only to the velocity component perpendicular to the sensitive face. Of course a basic requirement of any field measurement is that the instrument does not modify substantially the phenomenon to be measured. This is reasonable in our case, in view of the small dimensions of the transducer, and it has been checked during the tests described in paragraph 4.

The dynamic pressure associated to the relative water motion is obtained by Bernouilli’s principle. For an irrotational fluid (Batchelor, 1967, p. 508) this is written as

\[ \frac{\partial \varphi}{\partial t} + \frac{p}{\rho} + \frac{1}{2} \mathbf{U} \cdot \mathbf{U} = \text{const.}, \]

where \( \varphi \) is the velocity potential and \( \mathbf{U} \) is the velocity vector. If we assume the transducer, fixed in space, to be pointing against the positive, and hence sensitive only to, the horizontal component \( u, \) in the above equation \( \mathbf{U} \) can be substituted by \( u. \) The maximum over-pressure is found at the stagnation point and, by Bernouilli’s principle, it is given by

\[ p_1 = \frac{\rho u^2}{2} = \frac{a^2 \sigma^2 e^{-2kz} \cos^2 (kx - \sigma t) - \frac{1}{2} a^2 \sigma^2 e^{-2kz} \cos^2 (kx - \sigma t)}. \]

Note anyhow that these expressions are valid only for \( u \geq 0, \) as, when \( u \) is negative, we find a negative overpressure on the sensitive face of the transducer due to the wake effect around the transducer itself, while the above expression suggests \( p_1 > 0 \) independently of the sign of \( u. \) Wake effects are not directly deducible from Bernouilli’s principle, as this is strictly valid only for non viscous fluids.

The value of the depression with respect to the \( p_1 \) value specified above varies according to the local Reynolds’ number \( R_e. \) Rouse (1961, p. 221) describes the pressure distribution around a cylinder immersed in a uniform current. For the flow around a transducer, we are clearly above the potential regime, and the maximum \( R_e \) around it we find close to the sea surface in a wind wave field are of the order of \( 10^5. \) For this condition, Rouse reports a depression on the back of the cylinder equal to \( -p u^2 / 2, \) hence exactly the opposite of the \( p_1 \) specified above. Therefore, during a wave cycle, we must expect positive and negative overpressures on the sensitive face as a consequence of the relative motion of the water with respect to the transducer itself. With this in mind, and assuming \( u \) positive when flowing against the sensitive face, hence giving rise to a positive overpressure, \( p_1 \) can be rewritten in value and sign as
\[ P_1 = \rho \frac{|u|u}{2} = \rho \frac{a^2 \sigma^2 e^{-2kz}}{2} |\cos(kx - \sigma t)| \cos(kx - \sigma t), \quad (4) \]

where the product \( |\cos| \) takes now into account the direction of flow, and the consequent effect on the transducer. It is worthwhile to stress that (4) is not directly connected to the Bernoulli's equation, as this does not hold for viscous fluids, while (4) is an approximation consequent to the wake effect on the transducer. Besides, due to the turbulence present in the wake, (4) is strictly valid only for \( u < 0 \), and it is only a convenient approximation for our considerations when \( u > 0 \).

Keeping in mind the practical significance of (4), we can now estimate the percentage error due to \( p_1 \) by dividing (4) by (3). The result is

\[ \Phi_1 = \frac{a \sigma^2}{2} e^{-\sigma^2 z/4} \cos(kx - \sigma t), \]

or, as \( k = \sigma^2 / \gamma \),

\[ \Phi_1 = \frac{a}{2} |\Phi'| \cos(kx - \sigma t), \quad (5) \]

where

\[ \Phi' = \frac{a}{2} |k e^{-kz} \cos(kx - \sigma t) = \Phi' \cos(kx - \sigma t), \]

\[ \Phi'' = \frac{a}{2} |k e^{-kz} \]

\( \Phi'' \) is the maximum value of the relative error, and it is a function of wave number \( k \) and amplitude \( a \). It decreases monotonically with depth \( z \), hence, for given \( a \) and \( k \), reaches its maximum close to the surface. As a first approximation, neglecting for now the finite height of waves, the maximum is

\[ \Phi''_{\text{max}} = \frac{a}{2} \left( \frac{k}{L} \right)^2 \]

For \( a = 2m, L = 100m (f = 0.125 \text{ Hz}) \), this corresponds to \( \Phi''_{\text{max}} \approx 6 \% \).

Expression (6) can be conveniently rewritten in the form

\[ \Phi'' = \Phi' \frac{2z}{a} = k^2 e^{-kz}. \quad (7) \]

The corresponding curve is shown in Figure 1. From it, for given wave conditions and a given depth, the value of \( \Phi'' \), hence that of \( \Phi' \), can be directly deduced.

As previously specified, (4) and (5) have been obtained under the hypothesis that the transducer is sensitive only at the \( u \)-velocity component. With a different orientation, we find different expressions for the error, basically because of the different phase of the dynamic pressure with respect to that due to wave. Suppose for instance that the transducer is pointing vertically upwards, hence sensitive only to the \( w \)-component of water velocity. In this case (4) and (5) must be modified respectively as

\[ P_2 = \rho \frac{a^2 \sigma^2 e^{-2kz}}{2} |\sin(kx - \sigma t)\sin(kx - \sigma t)|, \quad (8) \]

\[ \Phi_2 = \Phi' \frac{\cos(kx - \sigma t)}{\sin(kx - \sigma t)}. \quad (9) \]

Consider now the case of a transducer with omnidirectional sensitivity, i.e. sensitive to the modulus \((u^2 + w^2)^{1/2}\) of the water velocity rather than only to a component of it. In this case (4) and (5) are modified as

\[ P_3 = \rho \frac{a^2 \sigma^2 e^{-2kz}}{2}, \quad (10) \]

\[ \Phi_3 = \frac{1}{\cos(kx - \sigma t)}. \quad (11) \]

Note that expressions (9) and (11) diverge when the cosine at their denominator approaches zero. This is consequent to the phase-shift between wave and dynamic pressures, that leads to a finite value of (8) and (10) when \( p \) (from (3)) is null.

Note also that, as in the linear theory the modulus of the velocity at a fixed position is constant, the omnidirectional sensitivity implies a constant error, as clearly seen from (10), where any dependence on time has disappeared. In this case, the dynamical effect of water motion would be a shift of the actual zero, with no influence on the apparent pressure oscillations due to waves.

The influence of the directional sensitivity is better visualized with a diagram. Considering only the variations respecting to the undisturbed hydrostatic value, the presence of a dynamic pressure means that, instead of the wave pressure \( p \), a transducer will measure a pressure \( P_i = p + p_i \) \((i = 1, 2, 3)\), where the \( p_i \) in the cases considered are given respectively by (4), (8) and (10). The
corresponding positive one. This does not modify the magnitude of the error. This would not be changed by the current, to reduce the corresponding percentage error to less than 1%, for an 8 second wave with 1 m amplitude.

Two things must be pointed out. First, for a more general validity, rather than (1), (2) and (3), we should use the corresponding formulas for intermediate depth conditions. This has not been done for the sake of simplicity, and because our aim was simply to show the order of magnitude of the error. This would not be changed by the use of the general formulas. Second, as previously specified, in writing (4) and (8) we have assumed that the negative overpressures are equal and opposite in sign with respect to the positive ones. This is not correct as the turbulence present in the wake leads to quite irregular signals, whose average value is smaller than the corresponding positive one. This does not modify the general conclusions, but it gives perhaps a preferential tendency to the error.

Thinking of practical measurements in the sea, one has to consider the likely presence of current. The dynamic pressure is not linear with respect to the particles velocity, hence the current interacts with the wave motion, further increasing the error. This is particularly true in the upper layers, close to the sea surface, where wind driven currents can reach very large values.

All the above shows that, if waves have to be measured by means of a pressure transducer and with the accuracy of a few percent, the dynamic effect of water motion cannot be neglected. As an example, even without considering any current, to reduce the corresponding percentage error to less than 1%, for an 8 second wave with 1 m amplitude, the transducer should be put at least 18 m below the surface. It is therefore worthwhile to devise a system capable to avoid the dynamical effect without altering the wave pressure. This has been done, and it is illustrated in the following paragraphs.

THE CHOSEN SOLUTION

Carson et al. (1975) quote several methods to avoid the dynamic effect of a current while measuring tide by pressure transducers. A disc or ellipsoid, picking up the signal from the center of their larger surface, give good results, but they are subjected to stalling when the current is inclined with respect to their main plane. The use of a static head tube, similar to a Pitot but without a front hole, is judged not to have good chances of long term survival in the marine environment. They propose another solution, consisting of a long pipe picking up the pressure through a small hole done laterally close to the outer end. The pipe aligns itself with the current so avoiding its dynamical effect. With this simple solution, Carson et al. certainly made a point on tide measurement, but we do not think this solution suitable for measurements in a wave field. The rapidly varying tridimensional velocity field would smash around the pipe, without even allowing the time of its alignment with the instantaneous current.

A common solution used in meteorology to avoid the dynamic effect of the wind, is a porous sphere, where the pressure is taken at its center. The application of such a solution to wave motion is problematic, however, for two reasons. A porous sphere implies a high filtering, suitable for the slow atmospheric variations, but that counteracts the aim of measuring the comparatively high frequencies present in a wave field. The sphere is subjected to a drag considerably more relevant than in the atmosphere. This implies an asymmetrical distribution of the pressure at its surface, which invalidate the principle of averaging the surface values.

An improvement of this system, more suitable for measurements under water, is to replace the porous sphere with a smooth waterproof plastic sheath. If the plastic is slack, and therefore its tension does not affect the ratio between internal and external pressures, the sheath has the same effect as the sphere, with the advantage of an almost immediate response. Besides, the adaptability of the soft sheath virtually eliminates any drag, making the transducer sensitive only to the wave pressure we want to measure.

TESTS

To check the applicability of the above solution, a series of tests were conducted with a Bell and Howell transducer (Fig. 3), measuring the dynamical effect of motion up to velocities of 100 cm/s. The measurements were made over the entire arc of incidence of the flow, with respect to the axis of the instrument, at ±30° intervals. The tests were carried out in the wave tank of the Institute of Oceanographic Sciences (Wormley, UK).

Figure 3
Pressure transducer used during the tests. During two of the series of tests, the transducer has been covered with a soft plastic sheath whose inner space (shadowed in the figure) was filled respectively with air and water.
The pressure transducer was fixed to one end of a pole, located vertically on the towing carriage. A graduated disc at the top and integral with the pole, allowed the choice of direction of the transducer, with respect to the direction of tow.

Although the diameter of the pole was reduced to limit interference with the measurements, it had to maintain a certain rigidity to exclude transverse vibrations due to wake vortices. Possible devices to limit oscillations were excluded in order not to increase the interference. The diameter was therefore chosen (≈ 10 mm) in conjunction with the length so as to produce visible transverse vibrations immediately above 80 cm/s.

Three possibilities were investigated: transducer without protection; with an air filled sheath; and a water filled sheath. The results are shown in Figures 4a, b, c, d. The figures also give the dynamic pressures theoretically felt by the transducer (continuous line). As previously pointed out, this is valid only for angles of incidence below 90°. For larger angles, the continuous line is symmetrical to the line for Φ below 90°, and is simply indicative without any practical correspondence.

![Figure 4](image)

Overpressure due to the relative motion of the water with respect to the pressure transducer. Different angles Ψ between its axis and the velocity direction have been considered. During two of the series of tests a soft plastic sheath, filled with air or water, has been used to cover the transducer. For angles Ψ < 90° the continuous line indicates the overpressure deduced from the potential theory. When Ψ > 90° the line is just indicative, symmetrical with respect to the previous case.

Analysis of the data show an irregular distribution of the dynamic pressure $p^\prime$ when the transducer has no cover. This, on its own, excludes the possibility in the field measurements of tracing back to the effective value of the pressure expressed by (3) by analyzing the results obtained, even if the current history at the transducer was known. The experimental values are mainly higher than the theoretical ones. This is apparently due to the shape of the transducer and to the turbulence present in the flow, with the consequent non linear effects. The implicit variability of results is confirmed by the presence of positive values with $\Phi > 90°$.

The dynamic pressures found when a sheath covers the instrument are extremely low and for the most part are concentrated near the zero line. Some isolated points are exceptions (Fig. 4a), owing possibly to the inherent limitations of the apparatus (pole vibration). The order of magnitude of $p^\prime$ is the same at various angles of incidence. On the average, the dynamic effect is more attenuated with the water filled sheath.

Some of the values given in the figures represent averages. In fact, when $u$ exceeds 80 cm/s, the signal loses its stability, producing oscillations, the amplitude of which increases with speed, and, for $u \geq 100$ cm/s, reaches 10 mm of water. These variations are probably the result of rapid fluctuations of the sheath. Their high frequency (over 10 Hz) is out of the range of wind waves, and it allows their filtering during the measurement.

Verification of the percentage error obtainable can be made as follows. For every speed $u$, there is a measured dynamic pressure $p^\prime$. Referring to the case of a transducer sensitive to the $u$-component, from (1) and (3) we see that

$$\frac{p}{u} = \frac{\gamma}{\sigma}$$

Hence, for each $u$ the percentage error is given by

$$\Phi = \frac{p^\prime}{p} = \frac{p^\prime}{\sigma} \frac{\gamma}{u}$$

A direct check of the results of the tests by means of (12) shows that, in the case of water filled sheath, $\Phi$ is less than 1% in 90% of the cases. A few higher values have been found in correspondence of the higher velocities. We think they were due to the vibrations of the vertical pole.

MEASUREMENTS IN THE SEA

The described solution was used during an extensive series of wave measurements (Cavaleri et al., 1978) carried out from the CNR oceanographie tower. A full description of the instrumental system is given by Cavaleri (1979), and it will be only summarized in this paper.

The tower, a strong four-legged structure, lays in the open sea in 16 m of depth, 8 miles off the coast of Venice. Power generators, living accommodations for 3-4 persons, standard meteo-oceanographie instruments in routine use are available on board. The instrumental system for detailed wave measurements includes a wave staff, all two electromagnetic currentmeters and two pressure transducers. With the exception of the wave staff, all the instruments are fixed to a rigid cart that can slide on two vertically tensed guide wires, set 8 m away from the legs.
experimental and theoretical energy levels. The wave directional distribution is estimated from the spectra. Fitness of theoretical and experimental pressure at a down depth (from one of the experiments) directly from Longuet-Higgins definition as the square root of the ratio between the peak period from 4 to 7 seconds.

Two main series of records are available, 16 and 20 records respectively, about 30 minutes of duration at 1 hour intervals. Each series includes the overall description of a storm, from its initial growing to the final decay. Significant wave height ranged from 0.5 to 2 m, peak period from 4 to 7 seconds.

For our actual aim, the results we care about are the pressure spectra compared to the surface ones and the wave directional distribution. The former is achieved by the contemporaneous measurement of the pressure at a known depth and of the surface elevation on the same vertical. Taking limited depth into account, surface spectra are transferred to the transducer depth by means of linear theory, and compared with the actual pressure spectra. Fitness of theoretical and experimental pressure spectra will vary with frequency $f$, and for each $f$, we define as $\alpha$ the square root of the ratio between the experimental and theoretical energy levels.

The wave directional distribution is estimated from the knowledge of the surface elevation, and the contemporaneous horizontal velocity field on the same vertical and at a down depth (from one of the electromagnetic currentmeters). The theory of the analysis follows directly from Longuet-Higgins et al. (1961), and it provides for each frequency the energy directional distribution filtered by an angular function. In our experiment, we found that a $\cos^2$ distribution was well representative of the actual angular spreading, with slightly narrower and wider distribution for low and high frequency respectively.

The $\alpha$ value for some of the records has been plotted against frequency in Figure 5. Each line refers to a single record. These have been grouped according to the depth of the transducers. Note that these results are fairly well representative of those obtained from all the other records. A few points are immediately evident: 1) there is a strong indication ($\alpha < 1$) that waves are more attenuated than foreseen by linear theory; 2) $\alpha$ shows approximately a linear dependence on frequency $f$; 3) the slope of this line depends on the depth of the transducer; 4) each group of records includes cases with highly different wave conditions, within the range previously specified. Hence the indication is that the slope of the line does not depend on the actual wave height.

For our actual aim, we point out that the immediate effect of the dynamic pressure would be to increase the apparent value of $\alpha$. This is clear from Figure 2, where the maximum variation of $P_1$ is always larger than that of $p$. The only exception is the omnidirectional sensitivity, which we think is unrealistic in practical measurements. But instead of large values of $\alpha$, we find $\alpha < 1$, which of course is against the presence of a dynamic pressure. Besides, and this is a basic point, we should expect the difference from the theory to be larger when the horizontal velocity $u$ due to waves, hence the consequent dynamic pressure, have their maximum value. This happens close to the surface, where on the contrary we find the best fit between theory and experiment, with $\alpha$ close to unit. A similar argument applies to the different wave height $H_3$ present in the same group of diagrams in Figure 5. These have been grouped according to the depth of the transducer. Different $H_3$ implies different orbital velocity and dynamic pressure, while such a tendency is not visible at all. Also any connection with the position of the spectral peak is absent, while we expect that the most influenced frequencies should be those where the energy is concentrated.

The same arguments apply to all the effects that are connected to the energy in the spectrum. This is true for the nonlinear interactions among the different frequencies, consequent to the nonlinearity of the dynamic pressure with respect to $u$. Their overall effect should be to increase the dynamic pressure, hence $\alpha$, but again no argument in their favour can be traced in the results.

Turbulence, as a random function superimposed to the orbital velocity, should act towards a further increase of $\alpha$. Apart from previous arguments, we point out that the effect of turbulence is also that of decreasing the coherence $R$ between the involved variable (pressure) and the reference one (surface elevation). Yefimov and
Khristoforov (1971 a, 1971 b) have clearly shown how the amount of turbulence present in the field is strictly connected and deducible from the coherence function. In our case, we found value of R very close to unit, and all our considerations have been limited to the range of the spectrum where R was greater than 0.99. This range covered in practice the energetical part of the spectrum, and it is showed in Figure 5 by the upper horizontal line, one for each record. While the presence of turbulence was clearly visible in the results from the analysis of the orbital velocities, its practical lackness in the pressure data indicates that the dynamic pressure was not sensed by the transducers.

To obtain expressions (1) to (3), we have previously assumed (§ 2) the existence of a monochromatic unidirectional wave. Besides being distributed among the different frequencies, wave energy has also an angular distribution, whose determination is a routine part of our data analysis. We found (Cavaleri et al., 1978) that a cos² function was well representative of the spreading. We do not think anyhow that this can have any influence in our actual considerations. The angular distribution does not affect the wave pressure, that is insensitive to the direction of motion, while it leads to a limited decrease of the rms value of u. We expect therefore a slight decrease of the corresponding $p_i$, which is unessential in the general argument about their possible presence.

Finally, the possible presence of a current superimposed to the wave motion has to be considered. Suppose a constant current $U$ is present, flowing in the main wave direction. The pressure transducer is pointing against the incoming waves, and the maximum orbital velocity at its depth is $u_m$. Assuming again the presence of a monochromatic wave, at each instant the horizontal velocity component $u'$ is given by

$$ u' = U + u_m \cos \theta = U + u. $$

The average dynamic pressure is proportional to $\langle u'^2 \rangle$, where $\langle \rangle$ denotes average over one or more wave periods. In the average, the double product disappears and we are left with

$$ \langle u'^2 \rangle = U^2 + \langle u^2 \rangle. $$

We see that the percentage error is of the order of $(U/u)^2$. Local velocity of the current is very low at the tower, and it was in any case measured for each record by the average output of the currentmeters. Typical value is of the order of 0.1 m, about $1/10$ of the orbital velocity. Hence the consequent percentage error is of the order of $1\%$, fully neglectable for our considerations.

CONCLUSIONS

The orbital motion of water particles due to waves disturbs the wave measurements by pressure transducers. The dynamic pressure consequent to water velocity is superimposed to the pressure field, causing error that can easily be of several percent. A system has been devised to avoid the effect of dynamic pressure. Such a system, consisting of a water filled plastic sheath surrounding the captive part of the transducer, has been tested both in a wave tank and in practical measurements in the field.

Tests in a wave tank, carried out towing the transducer at different speeds and at different angles with respect to the direction of motion, have shown that the dynamic pressure has been practically canceled. A very low almost random signal is consequent to the sheath oscillations at higher speed, and possibly to the limitations of the used system.

Results from field measurements are more difficult to analyze as the eventual presence of dynamic pressure $p_i$ would be at first concealed by other more dominant effects. Anyhow, its presence should lead to an increase of the pressure variations felt by the transducer, while the experimental results show an opposite tendency. The same is true for the nonlinear interactions among the different frequencies and for turbulence, whose presence has been proven by the analysis of the orbital velocity.

The effect of local current is found to be negligible, due to its limited value with respect to the orbital velocities. Dynamic pressure should be more evident at the frequency of the spectral peak, while no indication in this sense exists. Finally, $p_i$ should be larger where orbital velocities are larger, hence close to the surface and for higher waves. No suggestion in this direction has been found throughout the records.

The conclusion we draw is that the dynamic effect of water motion has been canceled, and the pressure transducers were picking up just the pressure field due to the presence of waves. The system devised is therefore effective in its use.

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