Vertical structure of the flow due to waves and currents

Laser-Doppler flow measurements for waves following or opposing a current

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G. Klopman
Executive’s summary

Changes in the mean horizontal-velocity profile in combined wave-current motion, outside the bottom boundary-layer, are essential for the correct prediction of cross-shore sediment transport outside the surf zone and the transport of dissolved matter, e.g. Klopman (1992).

To be able to verify mathematical and numerical models (see Klopman, 1992) experimental data is needed. This is especially the case with the vertical structure of the wave and turbulence Reynolds stresses where data is lacking. For this reason, a laboratory experiment was conducted to study the flow kinematics under combined wave-current motion, for waves propagating in the current direction and for waves opposing the current.

The wave-current facility in which the tests have been carried out is equipped with two computer-controlled wave boards, one generating waves and the other absorbing waves. Both wave boards have active wave-absorption systems which eliminate spurious waves. A constant discharge was provided by a flow-circulation circuit. Special care was taken in the design of the inflow and outflow structures, in order to introduce the current smoothly into the channel and to minimize unwanted reflections of the waves at the inflow and outflow.

Flow velocities were measured in one vertical cross-section of the channel, with two laser-Doppler velocimetry (LDV) systems, mounted at a fixed distance above each other. Water surface elevations were measured with six resistance-type wave-height meters, and the discharge was measured with an electro-magnetic flow (EMF) meter.

Tests were performed with mono-chromatic, bi-chromatic and random waves without current, following the current and opposing the current. Also a test series was performed for a steady current without waves.

A first data analysis was performed during the tests. The main results are:

- The measured data seems to be qualified for the study of mean velocities, wave orbital velocities, as well as wave and turbulence Reynolds-stresses under combined wave-current motion.
- The mean horizontal-velocity profile under combined wave-current motion is strongly affected by the presence of waves not only inside but also outside the wave bottom boundary-layer, which is in accordance within previous experiments. In the upper half of the water column the velocity shear is reduced and may even change sign in the case of waves following the current. Waves opposing the current increase the velocity shear in the upper half of the water column, see the figure alongside.
The change in the mean horizontal velocity profile seems to depend mainly on the wave energy and less on the shape of the wave-spectrum.

- The test series of waves without current show the well-known wave-induced streaming near the bed (Longuet-Higgins; 1953), in the direction of wave propagation. The mean horizontal-velocity varies almost linearly between the top of the wave bottom boundary-layer and wave trough level.

The level at which the flow velocity changes sign (see the figure below) seems to depend strongly on the spectral shape. This level increases when going from monochromatic via bi-chromatic to random waves.

![Diagram](image)

It is recommended that a more extensive data analysis be performed in order to obtain:

- mean velocity profiles corrected for apparent LDV cross-talk (see Section 2.3.2);
- the ensemble-averaged wave part of the velocity, as a function of the wave phase and height above the bed;
- ensemble-averaged wave and turbulence Reynolds stresses, as a function of the wave phase and height above the bed;
- mean wave and turbulence Reynolds stress profiles, and
- wave dissipation and free-surface slope.

**Organizational aspects**

The tests were performed in the "Scheldegoot" facility of Delft Hydraulics, location De Voorst, in the period of 21 September 1992 until 13 November 1992. The project team consisted of:

G. Klopman  
P. Pasterkamp  
P. Santbergen  
L. Tulp

Assistance for the operation of the LDV systems and other instruments was provided by J. Ardon and Th. de Haan. The report was drawn up by G. Klopman who also was the project leader.
Acknowledgements

This work has been undertaken as part of the Dutch Coastal Genesis Project and the MAST-2 G8 Coastal Morphodynamics research programme. It has been funded jointly by Rijkswaterstaat, Tidal Waters Division, The Netherlands, under contract no. DG-469 and by the Commission of the European Communities Directorate General for Science, Research and Development under contract no. MAS2-CT92-0027.

DELFt HYDRAULICS has funded the development and implementation of the closed flow-circulation circuit and the second wave-board in the wave-current facility ("Scheldegoot"), as well as the active wave absorption systems and second-order wave generation systems. These laboratory tools are essential for the successful generation of uniform and stable test conditions for this type of experiment.
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1 Introduction

1.1 General

The vertical structure of the mean flow under combined wave-current motion is strongly influenced by the interaction of the free-surface waves with the current, also outside the bottom boundary layer. Evidence of this can be found in previous experimental studies, e.g. Bakker & van Doorn (1978), Kemp & Simons (1982, 1983). These effects may have a considerable influence on the cross-shore sediment transport, see Klopman (1992).

For the numerical modelling of the wave-averaged three-dimensional flow under combined wave-current motion, information is needed on the bed shear-stresses in such flows, as well as the vertical structure of the wave and turbulence Reynolds stresses. This information has to be provided ultimately by mathematical models describing combined wave-current motion on an intra-wave scale, such as the multiple-scales perturbation-series $k-L$ model of Klopman (1992).

For the verification of these mathematical models, experimental data is needed. Previous experiments concentrated mostly on the mean and wave-part of the flow velocities in the bottom boundary-layer under mono-chromatic waves: Bakker & van Doorn (1978) studied waves and waves following the current in a wave-current channel (details can be found in van Doorn, 1981). Kemp & Simons (1982, 1983) performed experiments with waves both following and opposing the current, and without a current. Recently Simons et al. (1992) measured bed shear-stresses and flow kinematics for waves propagating orthogonal to the current direction in a wave-current basin. Random waves following as well as opposing the current were studied by van der Kaaij & Nieuwjaar (1987).

From the above we see that not much data is available outside the bottom boundary-layer, and that there is no experimental data at all about the vertical structure of the mean-flow driving-forces, and most data is for mono-chromatic waves. For this reason an experiment has been set up to measure these quantities.

1.2 Scope of the experiment

The experiment was conducted in a wave-current channel to assess the combined motion of a current with mono-chromatic, bi-chromatic and random waves. Test series both for waves following and waves opposing the current were performed, as well as test series for waves without a current and for a current without waves.

The objective of the experiment was:

- to provide accurate flow-kinematics data, suitable for determining wave and turbulence Reynolds stress distributions as a function of wave phase and distance to the bed, and
- to provide information about the influence of wave irregularity on the flow kinematics, by performing not only mono-chromatic but also bi-chromatic and random wave tests.
The wave-current facility was equipped with two wave boards at both ends of the channel, one of them generated waves and the other absorbed waves. So waves could be generated propagating in either direction of the channel. Both wave boards had active wave-absorption systems for absorbing spurious waves at both the carrier-wave frequencies and the subharmonic wave frequency. A constant discharge could be provided by a flow-circulation circuit. Before executing the actual tests, much effort had been put into a careful design of the inflow and outflow structures of the circuit, in order to provide both a smooth inflow and to avoid reflection of waves caused by the inflow-outflow structures at the same time.

The flow kinematics were measured at 40 to 50 points in one vertical near the centre of the channel, using two laser-Doppler velocimetry (LDV) systems, which could be moved in the vertical direction. Free-surface elevations along the channel were measured with six wave-height meters, and the discharge in the return pipe of the flow-circulation circuit was measured with an electro-magnetic flow (EMF) meter.

1.3 Outline of the report

In Section 2 we describe the experimental set-up, the wave-current facility, as well as the model geometry and the instrumentation. The LDV flow meters, including correction procedures for apparent cross-talk and frequency shifts are discussed and also the influence of seeding-particle sizes on measuring turbulence quantities.

Section 3 gives information on the actual experimental test programme, test procedures and data storage.

The results of the preliminary data-analysis during the experiment are given in Section 4. They show the suitability of the data for a more elaborate data analysis, and the influence of the waves on the mean flow, as well as results for the velocity-fluctuations.

Conclusions are drawn and recommendations are made in Section 5.
2 Experimental set-up

2.1 Wave-current facility

2.1.1 General

The experiments have been performed in a combined wave-current channel ("Scheldegoot") of Delft Hydraulics, location De Voorst, see Appendix A. This facility has a length of 46 m, a width of 1.0 m and a total depth of 1.2 m. The walls of the facility were made up of glass windows.

For the location of instruments in the facility, we adopted the following coordinate system (see also Figure 2.1):

- the $x$-direction was parallel to the channel axis, the positive $x$-direction was from wave board WB-1 (near the inflow) towards WB-2, and $x=0$ was located at the mean position of WB-1,
- the $y$-direction was in the horizontal plane parallel to the channel bed and orthogonal to the $x$-direction, the positive $y$-direction was to the right when looking from wave board WB-1 towards WB-2, and $y=0$ was located inside the channel at the glass window to the left,
- the $z$-direction was directed vertically upward, with $z=0$ located at the top of the concrete bed in the vertical where the flow kinematics were measured.

In contrast with the above coordinate system, the free-surface elevations are measured with respect to the still-water level (SWL), i.e. SWL corresponds with a zero free-surface elevation. The free-surface elevations were defined as positive when they lie above SWL.

The velocity components in the $x$-, $y$- and $z$-directions are called $u$, $v$ and $w$ respectively.

2.1.2 Wave generation and absorption

The facility was equipped with two wave boards, one at each end of the channel. Both wave boards were driven by hydraulic actuators and both were equipped with active wave-absorption systems. In the reported tests one of the wave boards generated waves, at the same time absorbing reflected waves. The wave board at the other end of the flume absorbed the waves. Mono-chromatic, bi-chromatic and random waves were generated, travelling in either direction along the flume.

The first wave board located at $x = 0$ m (wave board WB-1, near the inflow, see Figure 2.1 and Photograph 1) was a cradle-type wave board which could move in a combined translation/rotation motion. It was used only in the translatory mode during the experiment. As a result of the cradle-type support of the wave board, the board would move upward when it was not in its middle position. In order to prevent leakage below the wave board, which would deteriorate the wave board performance especially for long waves, this gap was closed by a small vertically-moving auxiliary board mounted near the bottom of the main wave board.

The second wave board at $x = 46$ m (wave board WB-2, see Figure 2.1 and Photograph 2) was a pure translatory-moving wave board.
Waves were generated by sending a control signal according to a second-order Stokes wave theory to one of the wave boards, see Klopman & van Leeuwen (1990) for a description of this system. This second-order wave board control includes corrections for the suppression of spurious free subharmonic and superharmonic components.

Both wave boards had an active wave-absorption system in order to prevent re-reflections of reflected waves against the wave board. The active wave-absorption systems were based on first-order short-wave theory. These systems were implemented on a personal computer (PC) running under MS-DOS. The systems absorbed both short and long free waves propagating towards the wave board.

A set of three wave gauges was attached flush with the front of the wave board and was moving with the wave board. The wave gauge signal (averaged over the three gauges) was sampled by the PC, after which it was used in the software feed-back system to compute a new position of the wave board. Also the control signal for generating waves was used in this feedback system.

This new position was sent to the wave board by the PC. Analog-to-digital (A/D) conversion of the measured wave-gauge signal, as well as digital-to-analog (D/A) conversion of the new wave-board position was done with the aid of a Keithley DAS-16 A/D-board in the PC.

Parameter settings of the active wave absorption systems were optimized before each test series in order to minimize the reflection coefficient of the wave boards.

2.1.3 Flow-circulation circuit

For the generation of a constant discharge the facility was equipped with a flow-circulation circuit, see Figure 2.1. This closed circuit consisted of two inflow/outflow boxes in the channel bottom located near the wave boards, a return pipe, a pump, a manually-operated butterfly valve and an electro-magnetic flow meter (EMF).

The flow in the channel was always directed from wave board WB-1 towards WB-2.

The inflow/outflow boxes were identical, see Figure 2.2. The length of the inflow and outflow was 1.43 m and the width was 1.00 m (equal to the channel width). Both the water inflow (Photograph 1) and outflow (Photograph 2) consisted of a box made of perforated plate and filled with marbles, the top of which was made flush with the channel bottom, see Photograph 3. The marbles redistributed the jets from the holes in the perforated plate, they reduced the turbulence of the jets and made the channel bed more or less horizontal for the waves. In this way a compromise has been found between a smooth and uniform inflow/outflow, and a minimum disturbance of the wave field.

The water outflow was situated in front of wave board WB-2. From here the water was pumped by a propeller-centrifugal pump through a pipe to the water inflow box in front of wave board WB-1, see Photograph 2. The pump is placed near the outflow, in order to reduce the suction-head due to the resistance in the outflow box. It gave time to the turbulence, generated by the pump, to decay in the return pipe to the inflow box. The pump was manufactured by Stork, type NU 28.5-25, and could produce a maximum discharge of 120 litre/s. The discharge could be controlled manually by a butterfly valve, the resulting discharge being very constant over time, irrespective of the presence or absence of waves in the channel. In the tests we used mean discharges of either 0 litre/s (pump off) or 80 litre/s.
The discharge in the pipe (and thus also in the flume) was measured by an electro-magnetic flow meter (EMF).

2.2 Model geometry

2.2.1 Concrete channel bed

A false bed with a concrete cover was constructed for three reasons:

a. The frame in which the glass windows were placed within the channel wall extended up to 0.10 m above the (steel) channel bed. But this frame also contributed to the channel bed rigidity. At the measuring section, the window frame could be lowered to 0.055 m. However, in order to be able to carry out measurements close to the channel bed a false bed had to be made.

b. This bed was roughened by pasting on coarse sand. The false bed with roughness can easily be removed. On the other hand, it would have been difficult to remove the sand afterwards when it would be pasted on the steel bottom directly.

c. At the measuring section the channel bottom had to be a bit convex, i.e. about 2 mm higher in the middle of the channel compared with the level near the glass windows. To be able to measure very close to the bed, the horizontal measuring beams of the LDV systems had to cross the channel from the laser until the receiving optics at the other side of the channel. In no way the beams should be blocked by the bed, or by sand pasted to the bed.

The false bed began at 0.3 m from the inflow and outflow boxes with slopes of 1 to 20 across a length of 1.2 m, and after which it became horizontal with a thickness of 0.06 m. Near the measuring section the bed was made slightly convex, as described above.

2.2.2 Bottom roughness

The bed was roughened using coarse sand, with a grain size of about 2 mm. The sand was pasted on the bed by means of a two-component paint on which the sand was sprinkled. After the paint had dried, the surplus of loose sand was removed. In order to determine the roughness of the bed, a test series with only current (without waves) was carried out. The results of this test series indicated a Nikuradse roughness of 1.2 mm (see Section 4).

2.2.3 Glass windows

At the measuring section (i.e. from \(x = 22\) m to \(x = 23\) m along the channel, see Figure 2.1), the existing window panes in the side walls could not be used for accurate LDV measurements, since they were scratched and had become blurred. Two new window panes of blank floated hardened glass were placed, one at each side of the channel. The panes were protected by a plastic foil during the construction of the concrete bed to avoid damage to the surface.
2.3 Instrumentation

The facility was instrumented with 6 wave height meters (WHM's), two 2-component laser-Doppler velocimetry flow-meters (LDV's), an electro-magnetic discharge meter (EMF), pen recorders and an oscilloscope (see also Figure 2.1). The signals of the wave height gauges, LDV's, wave paddle drive and pressure gauge were filtered, using a 50 Hz low-pass filter. The EMF was filtered using a 1 Hz low-pass filter. The water temperature was monitored regularly during the tests by thermometer readings. The data was collected on a PC with an A/D-conversion system.

2.3.1 Wave-height meters

The free surface elevation, with respect to SWL, was recorded with wave-height meters (WHM's). Six resistance-type twin-wire WHM's were placed in the model. From the available wave gauges, we selected the six wave gauges with the most linear calibration curves, in order to minimize non-linear bias errors in the measurement of subharmonic wave elevations. The specifications of the wave gauges, as they were used in the facility, were as follows:

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>DELFT HYDRAULICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>MK II</td>
</tr>
<tr>
<td>Measuring range</td>
<td>± 0.25 m</td>
</tr>
<tr>
<td>Linearity</td>
<td>± 0.5 % of full scale deflection</td>
</tr>
<tr>
<td>Static level stability</td>
<td>± 0.5 % of immersion depth</td>
</tr>
<tr>
<td>Output signal</td>
<td>± 10 V</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>60 Hz</td>
</tr>
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</table>

The immersion depth was approximately 0.25 m. The wave gauges were at least re-calibrated every week.

2.3.2 Laser-Doppler velocimetry systems

General

Flow kinematics were measured in one vertical, located at $x = 22.50$ m and $y = 0.50$ m, i.e. in the centre of the channel. Since our objective was the measurement of turbulence and wave-induced quantities and measurements close to the bed, laser-Doppler velocimetry (LDV) was a suitable method. In order to reduce the duration of the experiment, two systems were used to measure the horizontal and vertical flow velocities at two points in the same vertical simultaneously, see Photograph 4.

Instrument characteristics

The systems used were 3-beam 2-component LDV systems using the forward-scatter reference-beam method. The light scattered by particles in the measuring volume was analyzed by frequency counter-trackers to determine the velocity components. The LDV's measured two flow-velocity components in a vertical plane parallel to the wave propagation direction.
To be able to measure very close to the channel bed, the laser beams were arranged in such a way that the two reference beams were aligned in the horizontal plane, and the main beam directed slightly downward. After the beams intersected in the measuring volume, the main beam was no longer needed and may be blocked by the channel bed. For flow-velocity measurements, the light from the direction of the measuring beams had to be collected in the receiving optics at the other side of the flume. The LDV's could measure velocities 0.2 mm above the bed and higher.

This arrangement means that the flow meters did not measure the $u$- and $w$-components of the velocity directly, but instead measured two orthogonal velocity components under angles of 45° with the $x$-axis. From these the $u$- and $w$-velocity components were derived by electronics.

The measuring volume, roughly having an ellipsoidal shape, had to be small so that turbulence quantities close to the bed could be measured, and in order to prevent bias errors in the mean velocity. This is due to the fact that the flow meters measured velocities averaged over the measuring volume. The characteristic scale of the large turbulent eddies was of the order of the Von Kármán-constant ($\kappa = 0.4$) times the distance to the wall. If the measuring volume would be large compared to this eddy size, the measured velocities would be too smooth, i.e. turbulence velocity fluctuations would be underestimated.

Also, the curvature of the velocity profile would produce a bias error in the mean horizontal velocity near the bed if the measuring volume would be large. However, the problem of bias errors in the mean velocity was in general less restrictive than the above problem of turbulence under-estimation.

The measuring volume was reduced in size by the use of beam-expanders, which increase the distance between the three laser beams by a factor of 10/6. This allowed for an increase in the angle under which the laser beams intersected and also allowed for a reduction of the laser-beam diameter at the measuring volume. The resulting size of the measuring volume was an ellipsoid with a length of 1.5 mm (in $y$-direction) and a cross-beam diameter of 0.15 mm (in $x$- and $z$-direction).

The signal-processing equipment held the last detected meaningful value in case the signal drowned in the noise, i.e. by a so-called sample-and-hold system. This was important when analyzing data from a level lying above wave-trough level, as the flow meter did not get enough signal in air for making velocity measurements, due to a lack of seeding particles.
The characteristics of the flow meters can be found in Appendix B and in the table below:

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>DELFT HYDRAULICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Two-component</td>
</tr>
<tr>
<td></td>
<td>Forward-scatter</td>
</tr>
<tr>
<td></td>
<td>Reference beam</td>
</tr>
<tr>
<td>Stock nr.</td>
<td>LDFM02-IVM &amp; LDFM03-ODV</td>
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<tr>
<td>Laser</td>
<td>6 mW He-Ne (λa = 632.8 nm)</td>
</tr>
<tr>
<td>Front-lens focal length</td>
<td>≈ 59 mm between main and ref. beam</td>
</tr>
<tr>
<td>Distance between beams</td>
<td>≈ 83 mm between reference beams</td>
</tr>
<tr>
<td>(at front lens)</td>
<td>450 mm</td>
</tr>
<tr>
<td>Bragg-cell frequencies</td>
<td>40.2 MHz (main beam)</td>
</tr>
<tr>
<td>Beam expander</td>
<td>38.4 MHz (reference beam)</td>
</tr>
<tr>
<td>Light intensity</td>
<td>1.667 expansion factor</td>
</tr>
<tr>
<td></td>
<td>80% (main beam)</td>
</tr>
<tr>
<td>Measuring range</td>
<td>10% (each reference beam)</td>
</tr>
<tr>
<td>Repeatability</td>
<td>± 0.87 m/s (output range ± 10 V)</td>
</tr>
<tr>
<td>Non-linearity</td>
<td>± 0.5 mm/s</td>
</tr>
<tr>
<td>Measuring volume</td>
<td>&lt; 0.5 mm/s</td>
</tr>
<tr>
<td></td>
<td>1.5 x 0.15 x 0.15 mm³ ellipsoid</td>
</tr>
</tbody>
</table>

Flow meter LDFM02-IVM was mounted below LDFM03-ODV.

**Apparent cross-talk and frequency-shift corrections**

As mentioned above, the flow meters derived the u- and w-velocity signals from the signals measured under angles of approximately 45° with the x-direction, which we will call the A- and B-velocities, see Figure 2.3. From these, the flow meter processes approximations ̅ and ̃ for the real velocities u and w by addition and subtraction:

\[
\begin{align*}
V_\hat{u} &= \frac{+V_A - V_B}{\sqrt{2}}, \\
V_\hat{w} &= \frac{-V_A - V_B}{\sqrt{2}},
\end{align*}
\]

where \(V_\hat{u}, V_\hat{w}, V_A, \) and \(V_B\) are the voltages corresponding with the above velocities. The voltages \(V_\hat{u}\) and \(V_\hat{w}\) are the output of the flow meter, and they were sampled and stored.

However, it was found that the A- and B-direction calibration factors were different for one of the flow meters (LDFM02-IVM). Also, for this flow meter the A- and B-directions were not exactly orthogonal to each other.

This resulted in an apparent crosstalk between the \(\hat{u}\)- and \(\hat{w}\)-velocities. However, the 'real' velocities \(u\) and \(w\) could easily be reconstructed by using some simple algebra. The angle between the x-axis and the A-axis is called \(\alpha_A\), and the angle between the negative x-axis and the B-axis is called \(\alpha_B\), see Figure 2.3.
Then the following relation between the velocities exists:

\[ A = +u \cos(\alpha_A) - w \sin(\alpha_A), \]
\[ B = -u \cos(\alpha_B) - w \sin(\alpha_B), \]  

and the inverse relation is:

\[ u = \frac{1}{\sin(\alpha_A + \alpha_B)} [ A \sin(\alpha_B) - B \sin(\alpha_A)], \]
\[ w = \frac{1}{\sin(\alpha_A + \alpha_B)} [-A \cos(\alpha_B) - B \cos(\alpha_A)]. \]  

The angles \( \alpha_A \) and \( \alpha_B \) were measured with the aid of a theodolite, with the beam expanders removed, and with a front lens with a focal length of 500 mm instead of 450 mm. We assume that the beam expanders and front lenses do not affect the results. For LDFM02-IVM the measurements were repeated three times, with a repeated theodolite set-up. The following values for the angles were found:

<table>
<thead>
<tr>
<th></th>
<th>( \alpha_A (\degree) )</th>
<th>( \alpha_B (\degree) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDFM02-IVM</td>
<td>46.06</td>
<td>44.26</td>
</tr>
<tr>
<td></td>
<td>45.88</td>
<td>44.53</td>
</tr>
<tr>
<td></td>
<td>45.82</td>
<td>44.27</td>
</tr>
<tr>
<td>average</td>
<td>45.92</td>
<td>44.39</td>
</tr>
<tr>
<td>LDFM03-GIV</td>
<td>44.86</td>
<td>44.70</td>
</tr>
</tbody>
</table>

The following form of the calibration formula between the internal flow meter signals \( V_A \) and \( V_B \) (in V), and the corresponding velocities \( A \) and \( B \) (in m/s) is assumed:

\[ A = C_{0A} + C_{1A} V_A, \]
\[ B = C_{0B} + C_{1B} V_B, \]  

where \( C_{0A} \) and \( C_{0B} \) are zero shifts (in m/s), and \( C_{1A} \) and \( C_{1B} \) are the linear calibration coefficients (in m/s/V). The linear calibration coefficients \( C_1 \) were related to the angle between the main beam and the reference beam:

\[ C_1 = C_v \frac{\lambda_0}{2n \sin\left(\frac{\theta_n}{2}\right)}, \]

where \( \lambda_0 \) is the wave length of the laser-beam light, \( \theta_n \) is the angle between the reference beam and the main beam in a medium with refractive index \( n \), and \( C_v \) is the calibration coefficient (in Hz/V) of the receiving optics, i.e. between the detected Doppler frequency and the voltage output. The linear calibration coefficient \( C_1 \) is independent of the medium (e.g. air, glass or water) in which the measuring volume lies, and independent of the
presence of changes in medium which the light meets when travelling towards the measuring volume, provided that the normal to all medium interfaces is parallel to the front-lens axis. This is due to Snell's refraction law, applied to the current experimental set-up, see Figure 2.3:

\[
n_1 \sin \left( \frac{\theta_1}{2} \right) = n_2 \sin \left( \frac{\theta_2}{2} \right),
\]

(2.6)

with \( n_1 \) and \( n_2 \) the refractive indices in medium number 1 and 2 respectively, and \( \theta_1 \) and \( \theta_2 \) the angles between the main and reference beams in medium 1 and 2 respectively.

The angles \( \theta'_{AM} \) and \( \theta'_{BM} \) in air between the \( A \) - and \( B \)-reference beams and main beam \( M \) were again measured with a theodolite, with the beam expanders removed and with the front lenses of 500 mm focal length. The measured angles were:

<table>
<thead>
<tr>
<th></th>
<th>( \theta'_{AM} ) (°)</th>
<th>( \theta'_{BM} ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDFM02-IVM</td>
<td>3.94</td>
<td>4.05</td>
</tr>
<tr>
<td></td>
<td>3.96</td>
<td>4.05</td>
</tr>
<tr>
<td></td>
<td>3.94</td>
<td>4.04</td>
</tr>
<tr>
<td>average</td>
<td>3.95</td>
<td>4.05</td>
</tr>
<tr>
<td>LDFM03-ODV</td>
<td>4.02</td>
<td>4.03</td>
</tr>
</tbody>
</table>

These values were corrected for the presence of the beam expanders (expansion factor 1.667) and a front-lens focal length of 450 mm instead of 500 mm:

<table>
<thead>
<tr>
<th></th>
<th>( \theta_{AM} ) (°)</th>
<th>( \theta_{BM} ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDFM02-IVM</td>
<td>7.34</td>
<td>7.52</td>
</tr>
<tr>
<td>LDFM03-ODV</td>
<td>7.47</td>
<td>7.49</td>
</tr>
<tr>
<td>Design value</td>
<td>7.49</td>
<td>7.49</td>
</tr>
</tbody>
</table>

It can be seen that the values for the \( A \) - and \( B \)-direction of flow meter LDFM02-IVM deviate from each other and from the desired value. This was another cause for apparent cross talk between \( \hat{u} \) and \( \hat{\psi} \).

The linear calibration coefficients became, using Equation (2.5):

<table>
<thead>
<tr>
<th></th>
<th>( C_{1A} ) (m/s/V)</th>
<th>( C_{1B} ) (m/s/V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDFM02-IVM</td>
<td>0.0988</td>
<td>0.0965</td>
</tr>
<tr>
<td>LDFM03-ODV</td>
<td>0.0971</td>
<td>0.0969</td>
</tr>
<tr>
<td>Design value</td>
<td>0.0968</td>
<td>0.0968</td>
</tr>
</tbody>
</table>

since the refractive index of air is \( n_{air} = 1.0003 \) and \( C_v = 20 \text{ kHz/V} \).
It was also found that there is a difference between the transmitting-optics Bragg-cell frequencies and the receiving-optics down-mix frequencies, resulting in a zero shift in the velocities \( \dot{u} \) and \( \dot{w} \). The measured frequency shifts \( \Delta f_A \) and \( \Delta f_B \) are:

<table>
<thead>
<tr>
<th></th>
<th>( \Delta f_A ) (Hz)</th>
<th>( \Delta f_B ) (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDFM02-IVM</td>
<td>491</td>
<td>505</td>
</tr>
<tr>
<td>LDFM03-CDV</td>
<td>332</td>
<td>340</td>
</tr>
</tbody>
</table>

This can be corrected by using the \( C_0 \)-coefficients in the calibration formula, Equation (2.4). They become, due to \( C_0 = C_1 \Delta f/\dot{v} \):

<table>
<thead>
<tr>
<th></th>
<th>( C_{0a} ) (m/s)</th>
<th>( C_{0b} ) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDFM02-IVM</td>
<td>0.00243</td>
<td>0.00244</td>
</tr>
<tr>
<td>LDFM03-CDV</td>
<td>0.00161</td>
<td>0.00165</td>
</tr>
</tbody>
</table>

We will need the inverse of Equation (2.1), for the final correction formulas:

\[
V_A = \frac{-V_{\dot{u}} - V_{\dot{w}}}{\sqrt{2}}
\]

\[
V_B = \frac{+V_{\dot{a}} - V_{\dot{w}}}{\sqrt{2}}
\]

(2.7)

Given the measured voltages \( V_{\dot{a}} \) and \( V_{\dot{w}} \), the corrected velocities \( \dot{u} \) and \( \dot{w} \) can be computed by using the following steps:

- compute the voltages \( V_A \) and \( V_B \) from the measured voltages \( V_{\dot{a}} \) and \( V_{\dot{w}} \) using Equation (2.7),
- determine the velocities \( A \) and \( B \) using the calibration formula, Equation (2.4), with the calibration coefficients \( C_{0a}, C_{0b}, C_{1a} \) and \( C_{1b} \) according to above tables, and
- use Equation (2.3) and the measured angles \( \alpha_A \) and \( \alpha_B \) to compute the desired velocity components \( \dot{u} \) and \( \dot{w} \).

**Seeding particles**

The flow meters did not measure the actual fluid velocity, but only the velocity of suspended particles passing through the measuring volume, called seeding particles. From the application of LDV to air flows it is well known that the seeding particle-size has to be very small (of the order of 1 µm), if one is interested in measuring turbulence spectra or shock waves.

In the present experiment, water from the storage basin in the "Oosterscheldehal", where the facility is situated, was used to fill the channel and the flow-circulation circuit. The natural contaminations in the water, like dust and suspended sediment, were used as seeding particles. No additional seeding particles were added to the system. In the following we will study the implications of the particle diameter on the measured turbulent velocities.
The motion of a small particle, moving in fluid with a varying velocity is described in Hinze (1975), Eq. (5-198):

\[
m_p \frac{dV_p}{dt} = \lambda \left( V_f - V_p \right) + m_f \frac{dV_f}{dt} + \frac{1}{2} m_f \frac{d(V_f - V_p)}{dt} + \frac{3}{2} D^2 \rho_f \sqrt{\pi \nu} \int_{t_0}^{t} \frac{1}{\sqrt{t-t'}} \frac{d(V_f - V_p)}{dt'} \, dt' + F_e,
\]

(2.8)

where the assumption has been made that the particle is small, as compared to spatial variations in the flow. The meaning of the various quantities is that \( m_p = (1/6) \pi D^3 \rho_p \) is the mass of a spherical particle with diameter \( D \) and mass density \( \rho_p \), \( m_f = (1/6) \pi D^3 \rho_f \) is the mass of the fluid displaced by the particle with mass density \( \rho_f \), \( \lambda = 3 \pi \rho_f v D \) is a friction factor with \( v \) the kinematic viscosity of the fluid, \( F_e \) is an external force and \( t_0 \) is the starting time of the flow and particle motion.

The various terms in the above equation are as follows. On the left-hand side we have the particle acceleration force. On the right-hand side: the first term is Stokes's viscous resistance force, the second term is the Froude-Krylov force caused by the pressure gradient in the ambient accelerating fluid, the third term is due to the added mass of the particle, the fourth term is the Basset force due to the history of the flow and the last term describes an external potential force (e.g. a gravity force).

Since Equation (2.8) is linear, it is easy to determine the transfer function in the frequency domain between the particle motion and fluid motion. Assume there is no external force, and assume that the particle and flow oscillate sinusoidally:

\[
V_f = \text{Re} \{ \hat{V}_f e^{i\omega t} \},
\]

\[
V_p = \text{Re} \{ \hat{V}_p e^{i\omega t} \},
\]

(2.9)

with \( \text{Re} \{ \} \) meaning the real part of the expression between braces, \( \hat{V}_f \) and \( \hat{V}_p \) denoting the complex-valued velocity amplitudes of fluid and particle, \( \omega = 2\pi f \) the angular frequency (and \( f \) denoting the frequency). The complex-valued transfer function between particle and fluid motion becomes:

\[
H = \frac{\hat{V}_p}{\hat{V}_f} = \frac{i\omega \left( \frac{3}{2} + \frac{1}{2} \lambda D \right) + \lambda \left( 1 + \frac{1}{2} \beta D \right)}{i\omega \left[ m_p + m_f \left( \frac{1}{2} + \frac{1}{2} \frac{1}{\beta D} \right) \right] + \lambda \left( 1 + \frac{1}{2} \beta D \right)},
\]

(2.10)

with \( \beta = \sqrt{\omega/(2v)} \). It can easily be seen that \( H = 1 \) for all frequencies if \( \rho_f = \rho_p \).

However, this is normally not the case.

Figure 2.4 presents the transfer function for particles in air. When one wants to measure all velocity fluctuations, the maximum frequency in the turbulence spectrum is typically of the order 10 kHz to 100 kHz. To have a near unity response, the seeding particle size needs to be of the order of 1 \( \mu \text{m} \).
For fluid flows in water, the transfer function is presented in Figure 2.5. Due to the larger mass density of water, the situation is much better than in air. For high frequencies, the transfer function goes to the asymptotic value

$$\lim_{f \to \infty} H = \frac{3}{1 + 2 \frac{\rho_p}{\rho_f}}.$$  \hspace{1cm} (2.11)

Also the maximum phase lag is much smaller: of the order of $8^\circ$ for water and $80^\circ$ for air. The phase lag goes to zero for low frequencies because of the dominance of the viscous drag force (which tends to give the particles the same velocity as the fluid), and goes again to zero for high frequencies because of the balancing between inertia forces (including added mass effects).

In our laboratory experiment, the smallest eddies have sizes of the order of 0.1 mm (Kolmogorov micro-scale), and the highest frequencies are of the order 200 Hz. Seeding particles of the order of 30 $\mu$m are sufficient small to measure all the small-scale velocity fluctuations.

However, since we are only interested in averaged turbulence quantities such as the turbulence Reynolds shear-stress, only the energy-containing eddies have to be followed well by the particles, i.e. up to about 20 Hz. Seeding particles of the order of 100 $\mu$m are sufficiently small to actually follow the fluctuations at this frequency, and the above theory is still valid since the particles are much smaller than the Kolmogorov scale.

Since the particles in the water of the facility are mainly much smaller than 100 $\mu$m, it is concluded that no problems are to be expected due to the particle size.

**LDV traversing system**

The two LDV systems, including the transmitting and receiving optics, were placed on a traversing structure, which straddled the channel. Once the system was set up, i.e. after alignment of the transmitting and receiving optics, the whole traversing could be moved without need to re-align the LDV systems, since they were all attached to the same rigid structure. The structure rested on top of the side walls of the flume. The vertical distance between the measuring volumes of the two LDV systems was 250 mm, and they were aligned vertically above each other in the centre of the channel, see Photograph 4.

The rigidity of the system against vibrations was increased by attaching the heavy laser units and transmitting optics to a vertical steel cylinder, mounted on the floor next to the facility. The connection between the bar and the traversing system was formed by glide bearings, allowing for the vertical movement of the system. The unbalance in weight of the traversing system due to the heavy laser units and transmitting optics (which were all at one side of the channel) was reduced by the use of a counterweight, see Photograph 4.
The traversing system could be moved vertically up and down with the aid of a worm wheel with elevation indicator and nonius. During a series of tests, the traversing structure was only moved upward in order to prevent errors in the elevation due to hysteresis effects in the worm-wheel system. Before the start of a test series with a certain wave-current condition, the lower flow meter was first positioned a few millimetres below the channel bed, and then moved up to the first measuring position. In this way the elevations of the measuring volume could be reproduced within 0.1 mm. This was checked during tests by a separate elevation measurement using a point gauge.

2.3.3 Electro-magnetic discharge meter

One industrial electro-magnetic discharge meter was placed in the return pipe of the flow-circulation circuit. The discharge meter was used when a discharge in the facility had to be set, which was done by adjusting the position of a valve in the flow-circulation circuit until the desired discharge had been obtained. The specifications of the discharge meter as it was used in the facility were as follows:

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Endress + Hauser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>PULSMAG V DN200 mm</td>
</tr>
<tr>
<td>Measuring range</td>
<td>0...200 dm³/s</td>
</tr>
<tr>
<td>Output</td>
<td>0...10 V</td>
</tr>
<tr>
<td>Accuracy</td>
<td>± 1 % of the measured value from 20...100% of meas. range ± 0.2 % of measuring range from 0...20% of meas. range ± 0.1 % of the measuring range</td>
</tr>
<tr>
<td>Repeatability</td>
<td></td>
</tr>
</tbody>
</table>

The discharge meter was calibrated by the manufacturer. The signal of the discharge meter was low-pass filtered at 1 Hz and sampled by the data-acquisition system.

2.3.4 Oscilloscope

An oscilloscope was used as an aid in the tuning of the signal conditioners of the LDV systems. The oscilloscope was also used to monitor the quality of the LDV signals. The oscilloscope signals were not recorded.

2.3.5 Pen recorders

Pen recorders were used to make the four velocity signals visible during the tests. This was done to check the quality of the signals, e.g. the drop-out rate of the LDV systems. The pen recorders were not used to assess any quantitative results.
2.3.6 Filters

All signals (except the EMF) were low-pass filtered at 50 Hz before data-acquisition in order to prevent aliasing errors. The filters have the following characteristics:

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>DELFT HYDRAULICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>LP-03</td>
</tr>
<tr>
<td>Order</td>
<td>second order, constant time delay</td>
</tr>
<tr>
<td>Frequency range</td>
<td>50 Hz low-pass</td>
</tr>
<tr>
<td>Time delay</td>
<td>5 ms</td>
</tr>
<tr>
<td>Input/output</td>
<td>± 10 V</td>
</tr>
</tbody>
</table>

As mentioned in Section 2.3.3, the EMF was low-pass filtered at 1 Hz.

2.3.7 Temperature measurement

The water temperature was recorded regularly during the experiment. This was to check whether the water temperature (and thus the viscosity) had not changed too much as a result of heat input by the pump in the flow-circulation circuit. The used thermometer was:

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Hanna Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>ERSEKO</td>
</tr>
<tr>
<td>Accuracy</td>
<td>± 0.1 °C</td>
</tr>
</tbody>
</table>

2.3.8 Data acquisition and storage

Data acquisition and storage was performed by a PC (Compaq, 80486, 33 MHz) with a CED-1401 A/D-conversion intelligent subsystem, using the data-handling package AUKE/pc. This software package was developed to process data, measured at the various experimental facilities of DELFT HYDRAULICS.

The CED-1401 system used 12-bit A/D-conversion, i.e. the signal-input range of -10 V to +10 V is subdivided into $2^{12} = 4096$ intervals. Therefore, the signals are sampled with a resolution of approximately 5 mV.

The signals were sampled simultaneously at equidistant time intervals with a sample rate of 100 Hz, and written to the hard disk of the PC. The twelve sampled channels were:

- Six WHM surface-elevation signals, called GHM01 to GHM06,
- Four LDV velocity signals, called SHM01 to SHM04,
- One wave-board control signal, called SSN01, and
- One EMF discharge signal, called DBM01.

Each test consisted of the flow measurement for a specific wave-current situation, with the LDV systems measuring at a certain elevation. The data of each test was stored with AUKE/pc in two files, namely a data file (with extension .DAT) containing the sampled data and an
administration file (with extension .SEQ), containing information about the measured channels, calibration factors, etc.

During the tests, the data was also stored on a WORM laser drive (Write-Once, Read-Many times), to protect against data loss due to hard-disk failure. After the experiment, the data was copied from hard disk to optical disk and on Digital Audio Tape (DAT) for back-up.
3 Experimental test programme and procedures

3.1 Test Programme

3.1.1 Selection of wave and current conditions

The test conditions were chosen such that a common situation outside the surf zone near the Dutch coast was simulated. To be able to make comparisons with the mathematical model, non-breaking wave conditions were chosen. The following conditions were approximately chosen, the test model being 20 times smaller than prototype, using Froude scaling (i.e. length-scales by a factor of 20, and time- and velocity-scales by a factor of $\sqrt{20}$):

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Prototype</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean water depth</td>
<td>h</td>
<td>10 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5 m</td>
</tr>
<tr>
<td>Dominant wave period</td>
<td>$T_d$</td>
<td>7 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.4 s</td>
</tr>
<tr>
<td>RMS wave height</td>
<td>$H_{rms}$</td>
<td>2.4 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.12 m</td>
</tr>
<tr>
<td>Mean current velocity</td>
<td>$\bar{u}$</td>
<td>0.7 m/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.16 m/s</td>
</tr>
<tr>
<td>Roughness height</td>
<td>r</td>
<td>0.04 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 mm</td>
</tr>
</tbody>
</table>

All tests were performed with a still-water depth of 0.500 m above the horizontal concrete bed, measured at the cross-section where the velocities were measured ($x = 22.50$ m).

The channel bottom was roughened with coarse sand, as described in Section 2.2.2. The characteristic grain size was about 2 mm. From the current-alone tests, a Nikuradse equivalent sand-roughness was found of 1.2 mm. The unusual fact that the Nikuradse equivalent sand-roughness was smaller than the grain size (see e.g. Sleath, 1984, Section 1.16.3) must be ascribed to the fact that the sand was pasted on the channel bed, so that the grains were partially embedded in the adhesive.

Test series were performed with mono-chromatic waves, bi-chromatic waves and random waves, for waves following the current, opposing the current and without current. Also a test series was conducted for a current without waves.

An important criterium for the selection of wave period and wave height, especially for the mono-chromatic and bi-chromatic waves is the establishment of long-crested waves in the facility. For certain wave-current conditions cross waves may be generated due to non-linear resonant interactions between the waves travelling along the channel and cross-wave modes perpendicular to the wave propagation direction. Such an undesired effect may occur if twice the channel width is approximately equal to a multiple of a free wave length at a super-harmonic frequency of the mono-chromatic carrier-wave frequency.

However, by slightly changing the wave period, superharmonic resonance conditions vanish and the cross-waves disappear.

The wave and current conditions were chosen such that no cross-waves occurred.
The bi-chromatic carrier-wave frequencies were chosen in such a way, that they are multiples of the subharmonic frequency, i.e. the difference between the two carrier-wave frequencies. Therefore, the wave-board control signal repeats itself exactly after each wave-group period (the reciprocal of the subharmonic frequency).

The intention was to select wave conditions with approximately the same root-mean-square (rms) wave height (i.e. the same wave energy density), without breaking waves in the channel. Also the wave heights had to be as high as possible, in order to create measurable second-order effects. The mono-chromatic and bi-chromatic waves have the same rms wave height, the random wave height was slightly smaller in order to avoid wave breaking. The selected conditions were:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current</strong></td>
<td></td>
</tr>
<tr>
<td>Mean mass-transport velocity</td>
<td>0.10 m/s</td>
</tr>
<tr>
<td>Discharge</td>
<td>80 1/s</td>
</tr>
<tr>
<td><strong>Mono-chromatic waves</strong></td>
<td></td>
</tr>
<tr>
<td>Carrier wave period</td>
<td>1.44 s</td>
</tr>
<tr>
<td>Carrier wave amplitude</td>
<td>0.060 m</td>
</tr>
<tr>
<td><strong>Bi-chromatic waves</strong></td>
<td></td>
</tr>
<tr>
<td>Carrier wave period Component 1</td>
<td>1.70 s</td>
</tr>
<tr>
<td>Carrier wave period Component 2</td>
<td>1.36 s</td>
</tr>
<tr>
<td>Carrier wave amplitude Component 1</td>
<td>0.049 m</td>
</tr>
<tr>
<td>Carrier wave amplitude Component 2</td>
<td>0.035 m</td>
</tr>
<tr>
<td>Repetition time (wave-group period)</td>
<td>6.80 s</td>
</tr>
<tr>
<td>Number of waves per wave-group</td>
<td>4.5</td>
</tr>
<tr>
<td><strong>Random waves</strong></td>
<td></td>
</tr>
<tr>
<td>rms wave height</td>
<td>0.10 m</td>
</tr>
<tr>
<td>Spectral peak period</td>
<td>1.70 s</td>
</tr>
<tr>
<td>Mean wave period</td>
<td>1.44 s</td>
</tr>
<tr>
<td>Spectral shape (first order)</td>
<td>JONSWAP</td>
</tr>
<tr>
<td>Peak-enhancement factor</td>
<td>3.3</td>
</tr>
<tr>
<td>Repetition time</td>
<td>120.96 s</td>
</tr>
<tr>
<td>Number of waves per repetition time</td>
<td>84</td>
</tr>
</tbody>
</table>

Wave-board control signals were generated according to a second-order Stokes wave theory, based on a multiple-scales perturbation-series approach (Klopman & van Leeuwen, 1990). The control signals included subharmonic, superharmonic and amplitude-modulation corrections to the first-order signal, as well as corrections for the presence of the active wave-absorption systems. The wave-board control-signal for the random-wave generation repeated itself every 120.96 s.
Each test series consisted of flow-velocity measurements from very close to the channel bed up to the SWL. Test series names were made up of three or four characters:

- the first character was a hash ('#') character, followed by
- the second character was a 'W' for waves-without-current tests or a 'C' for combined wave-current tests or an 'S' for current-without-waves tests,
- the third one was an 'M' for mono-chromatic waves, a 'B' for bi-chromatic waves, an 'I' for random (irregular) waves, and an 'T' or 'P' for current-without-waves tests, and
- the fourth one was, in the case of combined wave-current tests a 'P' for waves following the flow and an 'N' for waves opposing the flow, in the case of waves-without-current a 'P' for waves travelling in the positive x-direction and an 'N' or 'O' for waves travelling in the negative x-direction, and no character for current-without-waves tests.

The following test series were conducted:

<table>
<thead>
<tr>
<th>Test series</th>
<th>Description</th>
<th>Current direction</th>
<th>Wave direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>#WBN</td>
<td>Mono-chromatic waves</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>#CMF</td>
<td>following current</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>#CMB</td>
<td>opposing current</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>#WBO</td>
<td>Bi-chromatic waves</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>#CBF</td>
<td>no current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#CBN</td>
<td>following current</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>#CIN</td>
<td>opposing current</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>#WIN</td>
<td>Random waves</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>#CIF</td>
<td>no current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#CIN</td>
<td>following current</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>#CIN</td>
<td>opposing current</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>#SPF</td>
<td>Current</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>#SPF</td>
<td>no waves</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Three additional test series were conducted: firstly, a series #WBN with bi-chromatic waves travelling in the negative x-direction without a current, but with different carrier-wave periods of 1.65 s and 1.32 s. However, cross waves were generated when adding an opposing current to these wave conditions, so different wave frequencies were chosen for the series #WBO, #CBN and #CBP. Secondly, a series #WMP with mono-chromatic waves travelling in the positive x-direction, without a current. Thirdly, a series #ST with only current, with the same conditions like those in the #SP-series. These last two series, #WMP and #ST, were performed at the start of the experiment, with the receiving optics and signal conditioners of the two LDV systems exchanged. However, the signal drop-out was much higher in this configuration, so it was decided to inter-change receiving optics and signal conditioners between the systems.
3.1.2 Test duration

The duration of the tests was based on estimates of the wave and turbulence time-scales. The test duration had to be long compared with the characteristic time-scales to be able to produce statistically reliable results.

The characteristic turbulence time-scale of the large eddies was estimated using dimensional analysis, see Tennekes & Lumley (1972). The mean water depth was taken as a characteristic length-scale $l_t$ for the turbulent boundary layer in a combined wave-current motion, and the characteristic velocity $u_t$ was taken to be about 10% of the mean mass-transport velocity. This resulted in the following estimate for the characteristic turbulence time-scale $T_t$:

$$T_t = \frac{l_t}{u_t} = \frac{0.5 \text{ m}}{0.015 \text{ m/s}} = 30 \text{ s},$$

(3.1)

and the test duration had to be long compared with $T_t$. The minimum test duration was thus chosen to be 600 s (20 times $T_t$).

Eddies larger than the Taylor micro-scale $\lambda_t$ (see Tennekes & Lumley, 1972, Section 3.2) contain most of the turbulence energy. The Taylor micro-scale is approximately

$$\lambda_t = \sqrt{\frac{15 \nu l_t}{A u_t}} = \sqrt{\frac{15 \cdot 10^{-6} \cdot 0.5}{1 \cdot 0.015}} = 0.02 \text{ m},$$

(3.2)

with the unknown constant $A$ set equal to 1 ($A$ is known to be order 1). The associated measured frequency when this micro-scale is swept along the LDV measuring volume with the mean velocity $\overline{u}$ is approximately

$$f_{\lambda_t} = \frac{\overline{u}}{\lambda_t} = \frac{0.16}{0.02} = 8 \text{ Hz}.$$  

(3.3)

So, most of the turbulence kinetic energy was to be found in the frequency band from 0.03 to 20 Hz. It can clearly be seen from this estimate that spectra of the turbulence and wave parts of the combined wave-current motion overlapped one another and cannot be separated by filtering in the frequency domain. If one does not want to rely on wave theories describing the relation between the free-surface elevation and the wave part of the flow kinematics, then it is necessary to use ensemble averaging to be able to separate the mean, wave and turbulence parts of the motion. The used sample rate of 100 Hz was much higher than the upper frequency-bound of 20 Hz for the most-energy containing eddies. Therefore, this sample rate was expected to be high enough for determining mean turbulence quantities like the ensemble-averaged turbulence Reynolds stresses.

The characteristic time-scales of the mono-chromatic and bi-chromatic waves (respectively 1.44 s and 6.8 s) were much smaller than the characteristic turbulence time-scale of the large eddies (30 s). Therefore, the test duration of the mono-chromatic and bi-chromatic wave and wave-current tests, as well as the current-alone tests, was set at 600 s. This is about 420 short-wave periods, and about 90 wave groups for the bi-chromatic waves).
The characteristic time-scale of the random wave tests is the time after which the wave-board control signal repeats itself, i.e. 120.96 s. The test duration of the random wave tests was chosen to be 1500 s (12 times the repetition time, about 1000 short-wave periods).

In summary, the chosen test durations were

<table>
<thead>
<tr>
<th>Condition</th>
<th>Test series</th>
<th>Duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current-alone</td>
<td>ESF (EST)</td>
<td>600</td>
</tr>
<tr>
<td>Mono-chromatic waves</td>
<td>NMS NCP NCIN (NMP)</td>
<td>600</td>
</tr>
<tr>
<td>Bi-chromatic waves</td>
<td>NBO NCP NCBN (NBNN)</td>
<td>600</td>
</tr>
<tr>
<td>Random waves</td>
<td>NWH NCIN NCIP</td>
<td>1500</td>
</tr>
</tbody>
</table>

### 3.1.3 Instrument positions

#### Wave-height meters

The six wave-height meter positions were determined by the requirement to be able to determine the incoming and reflected, free and bound waves at the carrier wave frequencies and at the subharmonic frequencies.

Two wave gauges (called GHM03 and GHM04) were positioned near the LDV measurement cross-section, to be able to reconstruct the free-surface elevation at the LDV measurement x-position and in order to assess incoming and reflected free-wave amplitudes of the carrier waves. Another two wave-height meters (GHM02 and GHM05) were placed further away, in order to compute the incoming-free, incoming-bound and reflected-free waves at the subharmonic frequencies (together with GHM03 or GHM04).

Two wave gauges (GHM01 and GHM06) were placed near the beginning and end of the flat concrete bed.

In Table 3.1 the positions of the wave-height meters during the different test series are presented.

The wave-height meters GHM03 and GHM04, which are relatively close to the LDV flow meters, are positioned off-centre in the flume. Therefore, the vortices shed from the wave-gauge rods do not reach and disturb the flow measurements in the centre of the channel.

#### Laser-Doppler velocimetry systems

The LDV flow meters were located at \( x = 22.50 \) m and \( y = 0.50 \) m, i.e. in the centre of the facility. The distance between the measuring volumes of the two LDV flow meters was fixed at 250 mm. Both flow meters could be moved vertically up and down simultaneously. The near-bed flow meter started to pick-up continuous velocity signals from 0.2 mm above the bed (and upward).

The vertical positions of the lower flow meter during the tests are given in Table 3.2.
Electro-magnetic discharge meter

The electro-magnetic discharge meter was placed into the return pipe of the flow-circulation system, about halfway between the outflow and inflow.

Thermometer

The sensor of the thermometer was permanently placed in the channel water, at about half the water depth and about 5 m downstream of the LDV measuring section.

3.1.4 Water temperature

The water temperature was recorded regularly during the tests, in order to check whether the water temperature (and thus the water viscosity) had changed much during a test series due to the heat produced by the pump in the flow-circulation circuit and the daily fluctuations in the hall temperature.

The kinematic viscosity of pure water can be found in e.g. Batchelor (1967, Appendix 1):

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Kinematic viscosity (10^{-6} \text{ m}^2/\text{s})</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.514</td>
</tr>
<tr>
<td>10</td>
<td>1.304</td>
</tr>
<tr>
<td>15</td>
<td>1.100</td>
</tr>
<tr>
<td>20</td>
<td>1.004</td>
</tr>
</tbody>
</table>

It was found that the changes in water temperature during a test series were small: of the order of one to three degrees Celsius. Therefore, temperature differences do not affect the interpretation of the experimental results.

The recorded water temperatures are presented in Table 3.3.

3.2 Test procedures

3.2.1 General

All tests within a series were recorded consecutively, before switching to another test condition. When a test series was not finished on the same day that it had been started, it was finished the next working day, without changing the position of the valve in the flow-circulation circuit.

If some tests within a series had to be repeated or in the case that some extra LDV measurements had to be carried out on other heights at the end of a test series, the procedure was as follows: firstly the LDV systems were moved downward until the measuring volume of the lower LDV flow meter was a few millimetres below the channel bed. And after this the LDV flow meters were moved upward until the desired elevation was reached. This was done to prevent hysteresis effects in the worm-wheel positioning system. Elevations were reproducible within 0.1 mm (see Subsection 2.3.2).
3.2.2 Start of data acquisition

Before we started the collecting data of the first test within a series, or the first test in the remainder of a series on the next working day, we waited at least half an hour to make sure that the test conditions had been sufficiently developed to a steady state.

Once being set, the discharge-controlling valve position and wave-board control settings were not altered before reaching the end of a test series.

3.2.3 Zero references

Regularly, but at least once a day before the start of the measurements, zero references were taken both of the wave-height meter signals and the discharge meter signal. The zero references were determined by the following procedure:

- The still water level in the channel was adjusted to the desired elevation of 500 mm above the concrete bed;
- If the zero-reference procedure was carried out before there had been any waves and/or current in the facility, the pump was switched on and operated for some time in order to mix the water in the facility. This was done to avoid errors in the wave-height meter zero-level readings due to thermal stratification;
- The pump and wave generation were turned off;
- Then we waited long enough so that we were sure that the water surface was still and horizontal;
- The instrument readings were adjusted to zero Volt as good as possible, by changing the corresponding potentiometer settings;
- The instrument signals were sampled and collected for 30 s;
- We used the time-averaged values of the sampled signals as a zero reference.

The zero references were stored in the administration files (with extension .SEQ) of each test, expressed in physical values. In these files, the zero-reference values for the LDV flow-meters are without meaning and should not be used.

3.2.4 Active wave-absorption system settings

The settings of the active wave-absorption system were optimized for minimum reflection before the start of each test series. The resulting reflection coefficients can be found in Section 4.5.

3.2.5 Wave-height meter calibration

The six wave-height meters were re-calibrated (at least) once a week, while placed in the facility. This was done by measuring the change in output voltage as a result of a 0.15 m change in the vertical gauge position.
The differences in the calibration factor of a certain wave gauge, from one calibration to the next calibration, were found to be typically less than one per cent.
3.2.6 Discharge reproducibility

The discharge reproduced very well from test to test within a test series, for a given setting of the used butterfly valve. Also, the discharge did not show oscillations with the carrier-wave frequency.

A very small reaction of the discharge to long wave action in the flume was found having a period of about 20.5 s, corresponding with a wavelength of 45 m which is about the channel length. Characteristic discharge amplitudes in this frequency range were of the order 0.1 l/s, which is very small as compared to the mean discharge of 80 l/s.

Some discharge statistics during three tests are given below:

<table>
<thead>
<tr>
<th>Test nr.</th>
<th>Average discharge (l/s)</th>
<th>Standard deviation (l/s)</th>
<th>Minimum (l/s)</th>
<th>Maximum (l/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#CMB01</td>
<td>80.48</td>
<td>0.17</td>
<td>79.76</td>
<td>81.17</td>
</tr>
<tr>
<td>#CMB02</td>
<td>80.50</td>
<td>0.18</td>
<td>79.76</td>
<td>81.11</td>
</tr>
<tr>
<td>#SF01</td>
<td>80.65</td>
<td>0.19</td>
<td>78.95</td>
<td>81.35</td>
</tr>
</tbody>
</table>

3.2.7 LDV system settings

The sensitivity of the LDV signal processors could be adjusted by means of a dial for each of the two measured velocity directions. An optimum had to be found between a low signal drop-out rate (insensitive settings) and accuracy (sensitive settings). The systems were set at a value lying close to the most sensitive settings at which no signal could be tracked. In general, signal drop-out occurred at most only a few times per test (apart from signal-drop out caused by the top laser falling dry above trough level).

In the case more signal drop-out was detected the test was repeated.

The search for the optimum sensitivity settings was facilitated by using an oscilloscope which served as a check on the quality of the flow-meter signals.

3.3 Data storage

3.3.1 Test-run identification

The naming convention for the test series is explained in Section 3.1.1.

The names of the individual runs within a test series were formed by adding a number to the series name, e.g. test run #CBN01, #CBN02 up to #CBN22. In general, increasing numbers mean an increasing elevation of the LDV systems above the channel bed. Repetitions of a test are named by adding an 'A', 'B', etc. to the test name, or by adding 10 or 20 to the run number (e.g. #WBN27 is a repetition of #WBN17). See Table 3.2 for a complete overview of test runs and repetitions.

The data of each test was stored into two files with DELFT HYDRAULICS' AUKE/pc package format, namely a data file with extension .DAT and a administration file with extension .SEQ.
3.3.2 Description of DAT-file

The signal voltages were sampled and converted into two-byte integers. The integers were stored in binary format into the DAT-file. This file was a direct-access file with a format according to Microsoft Fortran.

The conversion of the voltages to the two-byte integers was done by applying the formula:

\[
\text{store\_value} = \frac{\text{voltage\_value} \cdot (\text{highstored} - \text{lowstored})}{\text{highused} - \text{lowused}},
\]

(3.4)

where \text{voltage\_value} is the measured voltage, \text{store\_value} is the value as stored in the DAT-file and \text{highused}, \text{lowused}, \text{highstored} and \text{lowstored} are the values as found in the SEQ-file in the following line

'\text{A/D-CONVERSION, LOWSTORED=}lowstored, LOWUSED=}lowused, HIGHSTORED=}highstored, HIGHUSED=}highused'

where the italicized names actually are variables, which were kept constant during this experiment. Their constant values were:

<table>
<thead>
<tr>
<th>LOWUSED</th>
<th>-10 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGHUSED</td>
<td>+10 V</td>
</tr>
<tr>
<td>LOWSTORED</td>
<td>-32768</td>
</tr>
<tr>
<td>HIGHSTORED</td>
<td>+32752</td>
</tr>
</tbody>
</table>

This means that the measurable signal-voltage range lay between -10 V and +10 V, and that -10 V was mapped on the integer -32768 and +10 V was mapped on the integer +32752. Due to the 12-bit A/D-conversion, the resolution of the 2-byte integers was 4 bits, corresponding with steps of 16 in the integer values.

In every time step all the 12 signals were measured simultaneously and the corresponding 2-byte integer values were stored consecutively in the DAT-file. The sequence of the data per time step was according to the sequence of the instrument series as given in the SEQ-files. Thus, the first 12 samples were the values measured at time 0.00 s, the second 12 values were the values measured at time 0.01 s and so on.

The DAT-file size was exactly 1,440,000 byte (12 channels \( \times \) 600 s \( \times \) 100 Hz \( \times \) 2 byte/channel) for the mono-chromatic, bi-chromatic and current-only tests, and 3,600,000 byte (12 channels \( \times \) 1500 s \( \times \) 100 Hz \( \times \) 2 byte/channel) for the random wave tests.

3.3.3 Description of SEQ-file

The SEQ-files contained all the information required to convert the binary data in the DAT-file into physical values. In this section the content of the SEQ-file is described. An example SEQ-file can be found in Appendix C.
The SEQ-files were subdivided into sections, each beginning on a new line with a section heading (LOGGING, STO, GENERAL or SERIES) and ending on a new line with a corresponding END statement (e.g., END:LOGGING).

The first section, LOGGING, contained comments about the test without a fixed format that did not fit into the structure of the other sections.

The second section, STO (for storage) gave details of how the sampled data was stored. The third, GENERAL, described the project and gives information on the A/D conversion.

The fourth to the fifteenth section were all headed SERIES,instrument_name, where instrument_name was the name of the instrument. They were:

- GHM01 to GHM06 for the wave-height meters,
- SHM01 and SHM02 for the velocity components of the lower LDV flow meter,
- SHM03 and SHM04 for the velocity components of the upper LDV flow meter,
- SSN01 for the wave-board control signal and
- DBM01 for the EMF discharge meter.

Each section contained the measured zero level, the calibration factors, the dimensions of the measured quantity and the location of the instrument in the channel.

An example of a SEQ-file is shown in Appendix C, where also additional comments explaining the meaning of the statements can be found.

**3.3.4 Data conversion**

The data conversion to physical values of the 2-byte integers, stored in the binary DAT-files and described in the SEQ-files, is described below.

The data of all channels was stored consecutively per time step. The sequence of the data per time step was according to the sequence of the instrument series as given in the SEQ-files. Thus, the first 12 values were the values measured at time 0.00 s, the second 12 values were the values measured at time 0.01 s, and so on.

When the stored integer value (stored_value) of an instrument is read, the corresponding signal voltage (voltage_value) can be found by using the formula:

\[
\text{voltage\_value} = \text{store\_value} \cdot \frac{\text{highused\_lowused}}{\text{highstored\_lowstored}}
\]  

From the instrument signal-voltage, the physical value can be found with:

\[
\text{physical\_value} = C0 + C1 \cdot \text{voltage\_value} - \text{zerolevel\_value},
\]

where the calibration factors \(C0, C1\) and the zero reference \(\text{zerolevel\_value}\) are given in the SEQ-file in the appropriate instrument series-section. The zero-shift \(C0\) and the zero reference \(\text{zerolevel\_value}\) are optional. It depends on the application of the data whether these values should be added or not.
Note that the zero references for the LDV flow-meter signals are meaningless, since they must have a zero reference equal to zero due to the instrument characteristics. Note also that the calibration factors for the LDV flow meters are not correct. The flow velocities have to be obtained from the corresponding signal voltages by applying the algorithm described in Section 2.3.2.

In Table 3.4 the voltage values of the first eight time steps of run #CMP01 are given, as well as the corresponding physical values without and with the correction for the flow-meter signals as described in Section 2.3.2. They can be used as a check for the data-conversion procedure. These numbers are based on the information and calibration factors in the SEQ-file, apart from Table 3.4.c which is based on the flow-meter calibration factors in Section 2.3.2. The data was not corrected for the zero-reference values.

3.3.5 Data correction of LDV signals

The procedure for correcting the LDV signals for apparent cross-talk and zero-shifts is described in Section 2.3.2. The calibration factors for the LDV flow meters is also given in Section 2.3.2.
4 Preliminary data analysis

4.1 General

The presented results in this chapter were obtained during the experiment, and are only preliminary results to qualify the suitability of the data for a more thorough analysis.

Since the apparent cross-talk and Bragg-cell frequency-shift problems with the LDV flowmeters were only resolved after completion of the tests, the presented results covering the flow velocities were not corrected for these errors. The used linear calibration-factor for the flow meters of 0.0913 m/s/V, instead of the 'theoretical' value of 0.0968 m/s/V, resulted in an under-estimation of the velocities by approximately 7%.

The flow-meter signals in the region above the wave troughs were not corrected because the signal-processors hold the last measured meaningful value before the passage of the free-surface. From the fact that the main beam intersected the free surface when the free surface was about 35 mm above the measuring volume of the flow meters, it follows that the presented results are valid only below 35 mm under the wave-trough level.

4.2 Ensemble averaging

The spectra of the wave- and turbulence-parts of the flow-velocities do overlap one another, as described in Section 3.1.2. Therefore, if one does not want to rely on wave theories describing the wave part of the motion, ensemble averaging is the only possible method to separate the mean-, wave- and turbulence-parts of the motion.

Ensemble averages are determined by taking phase averages, i.e. the deterministic (mean and wave) part repeats itself after a certain duration $D$, which is equal to the carrier-wave period for the mono-chromatic waves, to the wave-group period for the bi-chromatic waves and to the wave-board control-signal repetition-time for the random waves. Successive parts of a signal are not necessarily independent realisations, since the turbulence time-scale may be larger than the duration $D$, see Section 3.1.2.

We define the phase average of a quantity $F(t)$ by:

$$\langle F(t) \rangle = \frac{1}{M} \sum_{m=0}^{M-1} F(t+mD) , \quad \text{for } t \in [0,D) ,$$

(4.1)

assuming there are $M$ repetitions of the wave-board control signal within a test.

The mean value of a quantity $F(t)$ is defined as the time average of the phase-averaged value:

$$\overline{F} = \frac{1}{D} \int_0^D \langle F(t) \rangle \, dt.$$ 

(4.2)
Now we can split quantities up into a mean part $\bar{F}$, a wave part $\tilde{F}(t)$ and a turbulence part $F'(t)$:

$$F(t) = \bar{F} + \tilde{F}(t) + F'(t),$$

with the wave part defined as

$$\tilde{F}(t) = \langle F(t) \rangle - \bar{F},$$

and the turbulence part as

$$F'(t) = F(t) - \langle F(t) \rangle.$$ 

From the definitions it can easily be shown that the mean values of the wave and turbulence parts, as well as the phase average of the turbulence part, are zero:

$$\bar{\tilde{F}(t)} = F'(t) = \langle F'(t) \rangle = 0.$$  

Defining the value of $F(t)$ to be zero when measured above the momentary free surface, phase averages and turbulence parts are defined in a sensible way above wave-trough level. However, it is by no means easy to define the mean and wave parts of a quantity $F(t)$ above wave-trough level in the case of combined wave-current motion. Since they are not needed in this report, no attempt has been made to define mean and turbulence parts above trough level.

### 4.3 Harmonic analysis

The flow-velocity data of the mono-chromatic and bi-chromatic test series was analyzed using harmonic analysis, which produces information about the mean and wave parts of the motion.

The deterministic part of a quantity, $\langle F(t) \rangle$, can be described by a Fourier series:

$$\langle F(t) \rangle = \sum_{n=1}^{\infty} a_n \cos \left(2\pi n \frac{t}{D} \right) + b_n \sin \left(2\pi n \frac{t}{D} \right),$$

(4.7)
with the cosine and sine Fourier-coefficients $a_n$ and $b_n$ defined by

$$a_n = \frac{2}{D} \int_0^D \langle F(t) \rangle \cos\left(2\pi n \frac{t}{D}\right) \, dt, \quad n = 1, 2, 3, \ldots,$$

$$b_n = \frac{2}{D} \int_0^D \langle F(t) \rangle \sin\left(2\pi n \frac{t}{D}\right) \, dt, \quad n = 1, 2, 3, \ldots,$$

(4.8)

$$a_0 = \frac{1}{D} \int_0^D \langle F(t) \rangle \, dt,$$

$$b_0 = 0,$$

with $a_0$ equal to the mean value of the signal.

The trapezoidal integration method was used as a numerical method for the approximation of the integrals from the sampled data.

The amplitude $c_n$ and phase $\varphi_n$ of the Fourier coefficients are defined as:

$$c_n = \sqrt{a_n^2 + b_n^2},$$

$$\tan(\varphi_n) = \frac{b_n}{a_n},$$

(4.9)

and the Fourier series (4.7) can also be written as

$$\langle F(t) \rangle = \sum_{n=1}^{\infty} c_n \cos\left(2\pi n \frac{t}{D} - \varphi_n\right).$$

(4.10)

In practice, we did not compute the Fourier coefficients from the phase-averaged signals, but we computed them on a wave-by-wave basis (here a wave means a period with duration $D$), and averaged the cosine and sine Fourier-coefficients afterwards. Since both the phase averaging and the Fourier-series decomposition are linear processes they may be interchanged without influencing the results.

### 4.4 Mean and turbulence quantities in steady current

The suitability of the test results for the determination of turbulence mean quantities such as Reynolds stresses, was assessed by analyzing the only-current test series #SP01. The power spectra of the velocity components, as well as the vertical profiles of the mean horizontal-velocity and the Reynolds stresses were determined.

A typical horizontal velocity power-spectrum is presented in Figure 4.1 on a double-logarithmic scale. In the inertial sub-range of the spectrum it is expected to be proportional to $f^{-5/3}$, with the frequency denoted by $f$, see e.g. Tennekes & Lumley (1972, Section 8.3).
For frequencies higher than approximately 5 Hz the spectral density varies with the frequency as $f^{-3}$. However, from theoretical estimates an upper limit to the inertial sub-range of about 20 Hz is expected. The reason of this more rapid decay of the power spectrum above 5 Hz is still unknown. Since nearly all of the turbulence energy occurs at lower frequencies it will only have a minor effect on the second-moments of the velocity, i.e. the Reynolds stresses.

At high frequencies, the spectra approach asymptotically to a constant noise level of $10^{-6} \text{ (m/s)}^2/\text{Hz}$. This is mainly due to the 12-bits resolution of the A/D-converters used in the data-acquisition system. Twelve-bits corresponds with a steps of about 0.5 mm/s in the sampled velocities, and a white noise level of the order of $5 \times 10^{-9} \text{ (m/s)}^2/\text{Hz}$.

Two peaks can be recognized within this white noise. A very sharp peak is present at 24.75 Hz. This is probably due to vibrations of the LDV systems caused by the pump operating at 1450 rpm (corresponding with 24.2 Hz) according to its specifications. A frequency of 24.75 corresponds with 1485 rpm. The second peak is less sharp and centered around 37 Hz. What may have caused this second peak is unknown. However, both peaks are irrelevant for the Reynolds stresses, since they only have a very small energy content.

Figure 4.2 presents the mean horizontal-velocity profile on a linear scale, and Figure 4.3 presents the same data on a semi-logarithmic scale. Near the bed the velocity profile is in close agreement with the logarithmic law-of-the-wall:

$$\frac{u^*}{u_*} = \frac{1}{\kappa} \ln \left( \frac{z}{z_0} \right), \quad (4.11)$$

with $u_* = \sqrt{\tau_b / \rho}$ the bed shear-stress velocity, $\tau_b$ the bottom shear stress, $\kappa = 0.4$ the Von Kármán constant and $z_0$ a bottom-roughness parameter describing an apparent zero-crossing level of the mean horizontal velocity.

The elevation $z = 0$ is the same for all results presented in this preliminary data analysis. It was chosen at the start of the experiment, producing a more or less linear velocity profile near the bed when plotting $u$ against $\ln z$, see Figure 4.3. This level can be optimized when a more thorough data analysis is performed.

By linear extrapolation of the velocities the zero-crossing level $z_0$ is estimated at $z_0 \approx 0.04 \text{ mm}$, corresponding with a Nikuradse roughness of $k_* = 30 \times z_0 \approx 1.2 \text{ mm}$. The bed shear-stress velocity is estimated to be about $u_* = 7.3 \text{ mm/s}$.

Information on some turbulence Reynolds stress components can be found in Figures 4.4 and 4.5.

The standard deviations $\sigma_u$ and $\sigma_w$ of the horizontal and vertical velocity, i.e. the square roots of the Reynolds normal stresses $u' u'$ and $w' w'$, are presented in Figure 4.4. Near the bed they tend to the values $\sigma_u = 0.017 \text{ m/s}$ and $\sigma_w = 0.0085 \text{ m/s}$, or when expressed in terms of the bed shear-stress velocity they become $\sigma_u = 2.3 u_*$ and $\sigma_w = 1.2 u_*$, which is in good agreement with other experimental results (see e.g. Hinze, 1976, Section 7.7). The Reynolds shear-stress $-u' w'$ is presented in Figure 4.5. From the conservation of horizontal momentum one can easily deduce that the sum of the viscous and Reynolds shear-stress should vary linearly with the distance from the bed, and be near zero at the free surface. The bed shear-stress is estimated to be $\tau_b / \rho = 46 \times 10^{-6} \text{ (m/s)}^2$, corresponding with a bed shear-stress velocity of $u_* = 6.7 \text{ mm/s}$, which is in good agreement with the value of 7.3 mm/s found from the mean horizontal-velocity profile.
The main conclusion is that it is indeed possible to extract meaningful information on the mean turbulence quantities from the data. It is very legitimate to expect that the same is true for the tests with waves and combined wave-current motion.

4.5 Incoming and reflected waves

The incoming and reflected waves in the mono-chromatic and bi-chromatic tests were determined with standard techniques to discriminate between respectively 2 and 3 different wave components using respectively 2 and 3 wave gauges, see e.g. Goda & Suzuki (1976). The effect of the current on the wave lengths was taken into account.

The incoming and reflected wave-components of the carrier waves were determined using the two wave-height meters GHM03 and GHM04 near the LDV measurement section. The results for the monochromatic waves are presented in Table 4.1.a, giving the amplitudes of the incoming and reflected waves, travelling with the celerity of free waves at the carrier-wave frequency, as well as the reflection coefficient (RC), defined as the ratio of the reflected and incoming wave-amplitudes times a 100%. It was found that the resulting reflection coefficient was about 7 to 8% or less for all tests.

The same was done for the bi-chromatic wave tests, see Table 4.1.b, but now for the two carrier-wave components, using again wave-height meters GHM03 and GHM04.

For the bi-chromatic wave tests, the incoming-free (i.f.), incoming-bound (i.b.) and reflected-free (r.f.) long-wave components were determined using the information from three wave-height meters. The results are presented in Table 4.1.b. It can be seen that the second-order wave generation is working quite well, since the incoming-free waves are much smaller than the incoming-bound waves, especially for the cases without current (the second-order wave-generation software does not account for the presence of a current).

The advantages of an active wave-absorber are clearly demonstrated by looking at the reflected-free wave amplitudes. The bound-long waves are absorbed to a large extend by the active wave-absorber. An even better performance is possible if the active wave-absorption software would be extended from first-order to second-order wave-theory.

The random wave-test results have not been analyzed yet for incoming and reflected waves, but reflection coefficients similar to those for the mono-chromatic and bi-chromatic wave tests are to be expected.

4.6 Mono-chromatic waves

4.6.1 General

Some of the results of the harmonic analysis, as applied to the horizontal velocities in mono-chromatic wave and wave-current test series, are presented in Figures 4.6 - 4.17. Fifty wave cycles within the 600 s of measured data were analyzed. The mean horizontal velocities and the horizontal-velocity amplitudes of the harmonic at the carrier-wave frequency are plotted in the figures.
4.6.2 Mean horizontal-velocity

Figures 4.6 - 4.8 present the mean horizontal-velocity profiles on a linear scale, and Figures 4.9 - 4.11 present the same data on a semi-logarithmic scale.

It should be noted, when interpreting the results of the wave-without-current test-series WMN (Figures 4.6 and 4.9), that the waves are propagating in the negative x-direction, and that a positive horizontal-velocity $u$ is in the direction opposite to the wave-propagation direction.

Therefore, the positive mean-velocities over the main part of the vertical are due to the undertow, and compensate for the mean mass-flux in the wave-propagation direction between wave-trough and wave-crest level. The mean velocity varies more or less linear with the distance to the bed, outside the wave-induced streaming layer near the bed. This is in agreement with results from previous experiments, e.g. Nadaoka & Kondoh (1982) outside the surf zone.

Near the bed, i.e. between $z = 1$ mm and 20 mm, we find a layer with wave-induced streaming, as first described by Longuet-Higgins (1953) for waves propagating over a smooth horizontal bed and for laminar flow. Very close to the bed, below $z = 1$ mm, the flow changes sign again, due to the local effects of individual sand grains at this particular vertical. Spatial averaging would have been necessary to average out the effects of individual grains. Since the LDV traversing mechanism did only allow for vertical movements, and not for horizontal ones, this has not been done.

The mean horizontal-velocity profiles for waves propagating with (CMP) and against (CMN) the current direction can be found in Figures 4.7 and 4.8, respectively. Comparison with Figure 4.2 for a current without waves clearly shows the influence of waves on the velocity shear in the upper half of the water column. Waves propagating with the current reduce the velocity shear $d\bar{u}/dz$ and even result in a negative shear whereas waves opposing the current increase the velocity shear. This observation is in good agreement with previous experiments into combined wave-current motion, e.g. van Doorn (1981), Kemp & Simons (1982, 1983), van der Kaaij & Nieuwjaar (1987).

Comparing the semi-logarithmic scaled Figures 4.10 and 4.11 for waves plus current with Figure 4.3 for waves without current clearly shows the reduction of near-bed velocities due to the presence of waves, which is also in agreement with other experiments. The independence of $z$ for the horizontal velocity below $z \approx 1$ mm is probably due to the effect of individual sand grains in the bed. Also the velocity shear $d\bar{u}/dz$ increases due to the increased mean bed shear-stress in the presence of waves.

4.6.3 Horizontal-velocity amplitude at carrier-wave frequency

Figures 4.12 - 4.14 show the amplitude of the horizontal velocity at the carrier-wave frequency, i.e. at the period $T = 1.44$ s, on a linear scale. Due to the phase-averaging, this is the amplitude of the wave-part $\bar{u}$ of the horizontal velocity, see Sections 4.2 and 4.3. Along the greater part of the vertical, the horizontal-velocity amplitude behaves like the cosine-hyperbolic shape, well-known from linear wave-theory. Near the bottom, a boundary layer is present.
From the semi-logarithmic scaled Figures 4.15 - 4.17 it can be seen that the horizontal-velocity amplitude behaves like the logarithmic law-of-the-wall near the bed. The roughness parameter $z_0$ is estimated to be approximately 0.02 mm for test-series #WMN and #CMN, and about 0.01 mm for test series #CMP. This is about 2 to 4 times smaller than the value found for the only-current test-series #SP (see Section 4.4). This may be due to the fact that the near-bed flow is more non-linear, i.e. the nearer the distance to the bed, the more energy is present in higher harmonics and less at the carrier wave frequency. However, a definite answer requires further analysis of the data.

Also, the velocity amplitude shows an overshoot before it approaches the value of the velocity outside the boundary layer. This behaviour is well-known both from oscillatory boundary-layer theory as well as from other experiments.

4.7 Bi-chromatic waves

4.7.1 Mean horizontal-velocity

The mean horizontal-velocity profiles for the bi-chromatic test-series are shown in the Figures 4.18 - 4.23. They were determined from the first 50 wave groups within a test. The effect of the bi-chromatic waves on the mean horizontal-velocity profile is similar to the mono-chromatic wave case, i.e. a reduced velocity-shear in the upper half of the water column for waves following the current (#CBP) and an increased velocity-shear for waves opposing the current (#CBN). This effect also agrees quantitatively quite well with the mono-chromatic wave tests, suggesting that the effect scales with the wave energy, and is less dependent on the spectral shape.

However, the zero-crossing height of the mean horizontal-velocity for bi-chromatic waves without current (#WBO) is much larger than for mono-chromatic waves: 0.05 m above the bed instead of 0.02 m.

4.7.2 Horizontal-velocity amplitude at carrier-wave frequencies

Also the horizontal-velocity amplitudes (determined from a harmonic analysis of 50 wave groups), as given in Figures 4.24 - 4.29 for the carrier-wave with period 1.36 s and in Figures 4.30 - 4.35 for the period 1.70 s, are similar in shape to those found for the mono-chromatic waves. So a cosine-hyperbolic shape is found outside the bottom boundary-layer, and the velocity amplitude behaves logarithmic with the distance to the bed in the bottom boundary-layer inner-region.

4.7.3 Horizontal-velocity amplitude at subharmonic wave frequency

Figures 4.36 - 4.41 present the horizontal-velocity amplitudes at the wave-group period of 6.80 s (being five times the carrier-wave period of 1.36 s and four times the carrier-wave period of 1.70 s). Outside the bottom-boundary layer the velocity amplitude is nearly constant, which is as expected from long-wave theory.
For waves opposing the current (#CBN, Figure 4.38) it was found that the velocity amplitude appeared to have a very strong overshoot at the edge of the boundary layer and some oscillations higher up in the vertical, while there is hardly an overshoot for the test series for waves without current (#WBO, Figure 4.36) and waves following the current (#CBP, Figure 4.37).

Compared with the carrier waves the subharmonic waves have a much thicker boundary layer: the height of the maximum velocity-amplitude overshoot is about 3 mm for the carrier-wave frequencies and about 15 mm for the subharmonic frequency. This is in agreement with the expectation (for mono-chromatic waves) that the boundary layer increases with the wave period, i.e. vorticity generated at the bed has more time to penetrate deeper before the flow direction changes, for longer wave-periods (for an infinite wave-period, i.e. a constant current, the boundary layer extends across the full water-depth). It is interesting to see that the same is true for such a complicated flow like bi-chromatic waves with a current.

The near-bed velocity-amplitude shear in the logarithmic part of the boundary layer is larger for the test-series with current (#CBP and #CBN) than for the test-series without current (#WBO), indicating a larger bottom shear-stress and larger apparent bottom-roughness for the cases with current.

4.8 Random waves

4.8.1 Mean horizontal-velocity

The mean horizontal-velocities are presented in Figures 4.42-4.44 on a linear scale, and in Figures 4.45-4.47 the same data is presented on a semi-logarithmic scale.

From the test-series without a current (#WIN) it can clearly be seen that the height above the bed at which the mean horizontal velocity changes sign, increases again: at \( z \approx 0.13 \) m (Figure 4.42), as compared with the mono-chromatic waves (\( z \approx 0.02 \) m, Figure 4.6) and bi-chromatic waves (\( z \approx 0.05 \) m, Figure 4.18). This indicates that this height depends strongly on the spectral shape of the free-surface waves. Again, the velocity is more or less varying linearly with the distance to the bed, outside the wave-induced streaming-layer.

The changes in the mean-velocity shear are qualitatively the same as those for the mono-chromatic and bi-chromatic wave tests. Quantitatively the changes in velocity shear are less strong for the random waves, but also the rms wave height (and thus the wave energy) of the random waves is smaller than that of the mono-chromatic and bi-chromatic waves.

4.8.2 Horizontal-velocity standard-deviation

The standard deviation of the horizontal velocity is given on a linear scale in Figures 4.48-4.50, and on a semi-logarithmic scale in Figures 4.51-4.53.

The standard deviation contains both the wave part \( \bar{u} \) and the turbulence part \( u' \) of the horizontal velocity, whereas the horizontal-velocity amplitudes for the mono-chromatic and bi-chromatic waves contain only the wave part \( \bar{u} \). Moreover, the standard deviation contains information condensed over all frequencies whereas the velocity amplitudes contain
information on specific frequencies. This should be kept in mind when trying to compare the results of the random waves with those of the mono-chromatic and bi-chromatic waves. Further analysis is necessary to be able to make good quantitative comparisons with the other wave types.

The results for the random waves show the same qualitative behaviour like those for the mono-chromatic and bi-chromatic waves: a cosine-hyperbolic like shape of the standard-deviation outside the wave bottom boundary-layer, a logarithmic variation of the standard-deviation very close to the bed and the overshoot in the velocity before attaining the value outside the bottom boundary-layer.
5 Conclusions and recommendations

5.1 Conclusions

The following conclusions can be drawn:

1. The data is qualified for the study of the ensemble-averaged mean- and wave-part of the flow velocities, as well as wave and turbulence Reynolds-stresses. This conclusion is based on the analysis of the measured turbulence spectra and Reynolds stress distributions in the case of a current without waves (see Section 4.4), and secondly on the discussion on the influence of the seeding particle size (see Section 2.3.2).

2. The waves do not only change the shape of the mean horizontal-velocity profile inside the wave boundary-layer, but also across the total water depth. In the upper half of the water column the velocity shear $\frac{du}{dz}$ is reduced in case of waves following the current (the velocity shear may even change sign). The velocity shear increases in case of waves opposing the current, see Sections 4.6 - 4.8. This observation is in agreement with previous experimental studies, e.g. Bakker & van Doorn (1978) or Kemp & Simons (1982, 1983).

3. This change in the mean horizontal-velocity profile seems to depend mainly on the wave energy, and less on the shape of the wave spectrum, since the mean velocities for the mono-chromatic and bi-chromatic wave tests are almost identical in the upper half of the water column, see Section 4.6.2 and 4.7.1. The mono-chromatic and bi-chromatic wave tests had the same rms wave height (and thus wave energy), whereas the random waves were slightly less energetic.

4. The results of the test series with mono-chromatic, bi-chromatic and random waves without a current (Sections 4.6.2, 4.7.1 and 4.8.1) show a steady wave-induced streaming near the bed in the wave propagation direction, which is in agreement with theory (Longuet-Higgins, 1953).

The same tests also show a near-linear variation in the mean horizontal velocity in the undertow layer from above the steady wave-induced streaming-layer up to the trough level. The level at which the mean horizontal-velocity changes sign seems to depend strongly on the spectral shape: namely at 0.02 m from the bed for the mono-chromatic waves, 0.05 m for the bi-chromatic ones and 0.13 m for the random waves (Section 4.8.1).

5. The measured LDV signals can be improved by applying a correction for the apparent cross-talk due to the misalignment of the laser-beams, and for the zero-shift due to the difference between the Bragg-cell frequency-shifts and the receiving-optics down-mix frequency, see Section 2.3.2.

6. The bed-roughness parameter $z_0$ for the horizontal-velocity amplitude in waves is about 2 to 4 times smaller than the $z_0$ for the current, see Section 4.6.3. This aspect needs further investigation.
7. The presence of waves reduces the near-bed mean horizontal-velocities, which is in agreement with other experiments (see Section 4.6.2).

8. In the bi-chromatic wave tests, the thickness of the boundary layer at subharmonic frequencies is larger than the boundary layer at the carrier-wave frequencies, see Section 4.7.3. This is in agreement with the expectation that the boundary layer thickness increases with the wave period.

5.2 Recommendations

The following recommendations for a more thorough data-analysis are made:

a. Mean-velocity profiles should be computed, corrected for apparent LDV cross-talk, frequency-shift errors and corrected for the presence of the free-surface in the splash zone (between wave trough and crest).

b. Ensemble-averaged velocity-signals should be determined as a function of the wave phase and height above the bed, which should be split into a mean and a wave part.

c. The ensemble-averaged wave and turbulence Reynolds-stresses should be constructed as a function of the wave phase and height above the bed, being the driving forces for the wave-part of the flow. The bed shear-stress should be determined as a function of the wave phase.

d. The wave and turbulence Reynolds-stresses should be averaged in order to determine the mean-flow driving forces.

e. Information on the wave dissipation and free-surface slope should be extracted from the wave-height meter signals.

f. The results with respect to the bottom shear stress (recommendation c) should be compared with the results of boundary-layer theories.

g. The mass-flux between wave trough and crest should be computed from the LDV measurements and EMP discharge signal.

Furthermore, it is important that the cause for the increased spectral decay of the LDV signals above 5 Hz be studied: although not too important for the determination of the turbulence Reynolds-stresses, it is nonetheless important for future experiments.
References


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Table 3.1  Position of the wave height meters during the different test series (in metres)
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Notes:

a. Test series #WMP has a different test numbering, but the same elevations as the other mono-chromatic series.
   The test numbers, in order of increasing elevation, are: #WMP01, 02, 25, 03, 35, 04, 45, 05 until 18, and 20.

b. In test #CMN12: 10.7 mm.

c. In test #CMN01: 0.45 mm.

d. Tests #WBN16 and 17 were repeated and these extra tests were called #WBN26 and 27 respectively.

e. These extra tests were done only in series #WBO.

f. In test #CIF02: 3.2 mm.

g. These extra tests were done only in series #WIN and #CIF.

h. In test series #ST two extra tests were done at elevations 0.2 mm (#ST01) and 0.3 mm (#ST015) above the bed.
   Test numbering in series #ST was different. Test numbers, in order of increasing elevation, are: #ST01, 015, 02 until 09, 095, 10 until 14. Tests #ST02 and #SP01 have the same elevation.

i. Tests #ST01, 02 and 03 were repeated. These extra tests are called #ST01A, 02A and 03A.

j. Test #SP11 was repeated and called #SP11A.

k. These tests were done only in series #SP.

Table 3.2 Vertical position of the lower LDV flow meter during the different test series (in millimetres above the bed)
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Table 3.3 Measured temperatures
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**Note:**

a. Test series continued here, on the next working day

Table 3.3 Measured temperatures (continued)
a. Integer values:

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<th>Time (s)</th>
<th>Wave-height meter (GBM)</th>
<th>Flow meter (SBM)</th>
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<tbody>
<tr>
<td>0.00</td>
<td>9440 9056 5040 5792 9280 9024 6784 208 13264 -592 -2688 21088</td>
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<td>9344 8976 4576 6176 9296 8928 6256 336 13264 -656 -2816 21088</td>
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<tr>
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<td>9248 8864 4144 6528 9280 8800 6358 304 13296 -800 -2944 21088</td>
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<tr>
<td>0.03</td>
<td>9072 8720 3664 8864 9232 8772 6875 272 13248 -1024 -3008 21104</td>
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<td>0.04</td>
<td>8912 8560 3216 7152 9168 8464 6288 184 13268 -1152 -3152 21088</td>
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<td>8720 8400 2768 7504 9040 8288 5824 122 13152 -1312 -3248 21088</td>
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<tr>
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<td>8496 8208 2320 7792 8880 8032 5888 64 13072 -1616 -3376 21088</td>
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<td>8256 7984 1872 8032 8704 7808 5760 80 12912 -1600 -3440 21088</td>
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</table>

b. Physical values (flow meter signals not corrected):

<table>
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<th>Flow meter (SBM)</th>
</tr>
</thead>
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<tr>
<td>0.00</td>
<td>0.0747 0.0681 0.0382 0.0432 0.0773 0.0679 0.1892 0.0660 0.3698 -0.0163 -0.8181 0.08049</td>
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<tr>
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<td>0.0740 0.0675 0.0347 0.0460 0.0774 0.0672 0.1745 0.0996 0.3698 -0.0181 -0.8571 0.08049</td>
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<td>0.0732 0.0667 0.0314 0.0487 0.0773 0.0662 0.1777 0.0987 0.3707 -0.0221 -0.8962 0.08049</td>
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<tr>
<td>0.03</td>
<td>0.0718 0.0656 0.0278 0.0512 0.0769 0.0653 0.1745 0.0978 0.3693 -0.0203 -0.9158 0.08056</td>
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<tr>
<td>0.04</td>
<td>0.0706 0.0644 0.0244 0.0533 0.0764 0.0637 0.1754 0.0920 0.3702 -0.0319 -0.9597 0.08049</td>
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<tr>
<td>0.05</td>
<td>0.0690 0.0632 0.0210 0.0559 0.0753 0.0624 0.1625 0.0956 0.3667 -0.0363 -0.9890 0.08049</td>
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<tr>
<td>0.06</td>
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<tr>
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c. Physical values (flow meter signals corrected):

<table>
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<th>Time (s)</th>
<th>Wave-height meter (GBM)</th>
<th>Flow meter (SBM)</th>
</tr>
</thead>
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<td>0.00</td>
<td>0.0747 0.0681 0.0382 0.0432 0.0773 0.0679 0.2029 -0.0021 0.3914 -0.0206 -0.8181 0.08049</td>
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<tr>
<td>0.01</td>
<td>0.0740 0.0675 0.0347 0.0460 0.0774 0.0672 0.1871 0.0021 0.3914 -0.0225 -0.8571 0.08049</td>
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<tr>
<td>0.03</td>
<td>0.0718 0.0656 0.0278 0.0512 0.0769 0.0653 0.1871 0.0002 0.3910 -0.0335 -0.9158 0.08056</td>
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<tr>
<td>0.04</td>
<td>0.0706 0.0644 0.0244 0.0533 0.0764 0.0637 0.1881 -0.0060 0.3919 -0.0373 -0.9597 0.08049</td>
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<tr>
<td>0.05</td>
<td>0.0690 0.0632 0.0210 0.0559 0.0753 0.0624 0.1742 -0.0019 0.3881 -0.0420 -0.9890 0.08049</td>
<td></td>
</tr>
<tr>
<td>0.06</td>
<td>0.0673 0.0618 0.0176 0.0581 0.0740 0.0604 0.1761 -0.0057 0.3858 -0.0520 -1.0281 0.08049</td>
<td></td>
</tr>
<tr>
<td>0.07</td>
<td>0.0654 0.0601 0.0142 0.0599 0.0725 0.0588 0.1723 -0.0051 0.3810 -0.0506 -1.0476 0.08049</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.4 Voltage values and physical values of all channels for the first eight
time steps of test #CMP01
### a. Mono-chromatic wave tests

<table>
<thead>
<tr>
<th>Test nr.</th>
<th>Amplitudes</th>
<th>RC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inc. (mm)</td>
<td>Refl. (mm)</td>
</tr>
<tr>
<td>#WMN01</td>
<td>59.4</td>
<td>4.5</td>
</tr>
<tr>
<td>#WMN06</td>
<td>59.4</td>
<td>4.3</td>
</tr>
<tr>
<td>#WMN11</td>
<td>59.4</td>
<td>4.4</td>
</tr>
<tr>
<td>#WMN16</td>
<td>59.6</td>
<td>4.9</td>
</tr>
<tr>
<td>#CMP01</td>
<td>59.9</td>
<td>4.5</td>
</tr>
<tr>
<td>#CMP06</td>
<td>59.9</td>
<td>4.7</td>
</tr>
<tr>
<td>#CMP11</td>
<td>59.8</td>
<td>4.4</td>
</tr>
<tr>
<td>#CMP22</td>
<td>59.5</td>
<td>4.8</td>
</tr>
<tr>
<td>#CMN01</td>
<td>60.0</td>
<td>4.7</td>
</tr>
<tr>
<td>#CMN06</td>
<td>60.2</td>
<td>4.6</td>
</tr>
<tr>
<td>#CMN11</td>
<td>60.0</td>
<td>4.6</td>
</tr>
<tr>
<td>#WMP01</td>
<td>60.9</td>
<td>4.2</td>
</tr>
<tr>
<td>#WMP06</td>
<td>60.8</td>
<td>4.1</td>
</tr>
<tr>
<td>#WMP11</td>
<td>60.9</td>
<td>4.1</td>
</tr>
</tbody>
</table>

### b. Bi-chromatic wave tests

<table>
<thead>
<tr>
<th>Test nr.</th>
<th>Component 1</th>
<th>Component 2</th>
<th>Subharmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>amplitudes</td>
<td>RC</td>
<td>amplitudes</td>
</tr>
<tr>
<td></td>
<td>inc. (mm)</td>
<td>refl. (mm)</td>
<td>(%)</td>
</tr>
<tr>
<td>#WBO03</td>
<td>48.8</td>
<td>3.7</td>
<td>7.5</td>
</tr>
<tr>
<td>#WBO11</td>
<td>48.8</td>
<td>3.7</td>
<td>7.5</td>
</tr>
<tr>
<td>#WBO25</td>
<td>48.9</td>
<td>3.7</td>
<td>7.6</td>
</tr>
<tr>
<td>#CBP01</td>
<td>49.0</td>
<td>2.3</td>
<td>4.7</td>
</tr>
<tr>
<td>#CBP06</td>
<td>49.0</td>
<td>2.3</td>
<td>4.6</td>
</tr>
<tr>
<td>#CBP11</td>
<td>49.0</td>
<td>2.3</td>
<td>4.7</td>
</tr>
<tr>
<td>#CBP16</td>
<td>49.0</td>
<td>2.3</td>
<td>4.6</td>
</tr>
<tr>
<td>#CBP22</td>
<td>49.1</td>
<td>2.3</td>
<td>4.7</td>
</tr>
<tr>
<td>#CBN01</td>
<td>48.5</td>
<td>2.0</td>
<td>4.1</td>
</tr>
<tr>
<td>#CBN06</td>
<td>48.4</td>
<td>1.9</td>
<td>3.9</td>
</tr>
<tr>
<td>#CBN12</td>
<td>48.5</td>
<td>1.8</td>
<td>3.8</td>
</tr>
<tr>
<td>#CBN17</td>
<td>48.5</td>
<td>1.8</td>
<td>3.7</td>
</tr>
<tr>
<td>#CBN22</td>
<td>48.6</td>
<td>1.9</td>
<td>3.8</td>
</tr>
<tr>
<td>#WBN01</td>
<td>48.4</td>
<td>3.0</td>
<td>6.3</td>
</tr>
<tr>
<td>#WBN06</td>
<td>48.4</td>
<td>3.0</td>
<td>6.2</td>
</tr>
<tr>
<td>#WBN11</td>
<td>48.3</td>
<td>3.0</td>
<td>6.3</td>
</tr>
<tr>
<td>#WBN17</td>
<td>48.4</td>
<td>2.9</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Table 4.1 Incident and reflected waves
a. measuring directions

b. beam optics
fluid mass density \( \rho_f = 1.2 \) kg/m\(^3\)
particle mass density \( \rho_p = 2000 \) kg/m\(^3\)
kinematic viscosity \( \nu = 1.4 \times 10^{-5} \) m\(^2\)/s
ATTENUATION

\[
\text{abs } |H| (-)
\]

\[
\text{f (Hz)}
\]

PHASE LAG

\[
\text{arg } [H] \text{ (deg.)}
\]

\[
\text{f (Hz)}
\]

- fluid mass density \( \rho_f = 1000 \text{ kg/m}^3 \)
- particle mass density \( \rho_p = 2000 \text{ kg/m}^3 \)
- kinematic viscosity \( \nu = 1.2 \times 10^{-6} \text{ m}^2/\text{s} \)

TRANSFER FUNCTION BETWEEN PARTICLE AND FLUID MOTION

DELTFT HYDRAULICS
AUTOSPECTRUM OF THE HORIZONTAL VELOCITY SIGNAL AT Z = 0.250 m

DELFt HYDRAULICS

H 840 FIG. 4.1
COASTAL GENESIS / MAST-2
MEAN HORIZONTAL VELOCITY PROFILE
CURRENT

DELFt HYDRAULICS
STANDARD DEVIATION OF HORIZONTAL AND VERTICAL VELOCITY

DELFT HYDRAULICS

#SP

H 840 FIG. 4.4
COASTAL GENESIS / MAST-2
MEAN HORIZONTAL VELOCITY PROFILE
MONOCHROMATIC WAVES

DELFt HYDRAULICS
COASTAL GENESIS / MAST-2
MEAN HORIZONTAL VELOCITY PROFILE
MONOCHROMATIC WAVES, OPPOSING CURRENT

DELFt HYDRAULICS
COASTAL GENESIS / MAST-2
HORIZONTAL VELOCITY AMPLITUDE PROFILE
MONOCHROMATIC WAVES, FOLLOWING CURRENT

DELFt HYDRAULICS

#CMP

H0840.30 FIG. 4.13
CARRIER WAVE  $T=1.36 \text{ s}$

$Z \text{ (m)}$

$U \text{ (m/s)}$

COASTAL GENESIS / MAST-2
HORIZONTAL VELOCITY AMPLITUDE PROFILE
BICHROMATIC WAVES, OPPOSING CURRENT

DELFt HYDRAULICS

#CBN

H0840.30 FIG. 4.26
CARRIER WAVE  T=1.36 s

COASTAL GENESIS / MAST-2
HORIZONTAL VELOCITY AMPLITUDE PROFILE
BICROMATIC WAVES, OPPOSING CURRENT

DELFt HYDRAULICS
CARRIER WAVE  \( T = 1.70 \) s

COASTAL GENESIS / MAST-2
HORIZONTAL VELOCITY AMPLITUDE PROFILE
BICHROMATIC WAVES

DELT HYDRAULICS
CARRIER WAVE $T = 1.70 \text{ s}$

COASTAL GENESIS / MAST-2
HORIZONTAL VELOCITY AMPLITUDE PROFILE
BICHROMATIC WAVES

DELT HYDRAULICS
CARRIER WAVE  T=1.70 s

COASTAL GENESIS / MAST-2
HORIZONTAL VELOCITY AMPLITUDE PROFILE
BICHROMATIC WAVES, FOLLOWING CURRENT

DELFt HYDRAULICS

#CBP

H0840.30 FIG. 4.34
CARRIER WAVE  T=1.70 s

COASTAL GENESIS / MAST-2
HORIZONTAL VELOCITY AMPLITUDE PROFILE
BICHROMATIC WAVES, OPPOSING CURRENT

DELFt HYDRAULICS

#CBN

H0840.30 FIG. 4.35
SUBHARMONIC $T=6.80\; s$

COASTAL GENESIS / MAST-2
HORIZONTAL VELOCITY AMPLITUDE PROFILE
BICHROMATIC WAVES, OPPOSING CURRENT

DELFt HYDRAULICS
Photo 1  Wave board WB-1 and inflow structure

Photo 2  Wave board WB-2, outflow structure, pump and valve
Photo 3  Inflow/outflow box with marbles and protective netting

Photo 4  LDV systems and counterweight
Appendix A

Description of wave-current facility "Scheldegoot"
Wave flume "Scheldegoot"

The "Scheldegoot" facility of DELFT HYDRAULICS is a wave flume with a wave maker capable of generating both periodic and random waves. The translation/rotation ratio for the wave board motion is adjustable. The wave generator is equipped with a patented device to prevent reflection against the wave board and also to avoid undesired long-periodical waves. At the back of the flume a second wave board is installed for active wave absorption.

For wave board control, data acquisition and data processing DELFT HYDRAULICS' time-series generating and processing package AUKE/pc is used. Wave board control for random second-order waves is available. The flume is equipped with a pump system enabling the simulation of currents, so that the combination of waves and current can be studied too.

**relevant data:**
- **wave flume**
  - length: 55 m
  - width: 1 m
  - height: 1.2 m.

- **wave maker**
  - width: 1 m
  - height: 1.2 m
  - minimum water depth 0.25 m
  - maximum water depth 1.0 m
  - cradle-type wave board
  - hydraulically driven system
  - control signal is a digitized time series.

**wave characteristics**
- wave frequencies between 0 and 2 Hz
- maximum wave height $H_{max} = 0.4$ m for $f = 0.5$ Hz
- maximum significant wave height $H_s > 0.25$ m for $T_p = 1.9$ s
- wave damping: spending beach.

**pump capacity**
- maximum pump capacity 120 l/s.
Appendix B

Description of laser-Doppler velocimetry system
LDFM
Laser Doppler Flow Meter
An instrument for detailed velocity analysis
The applications mentioned on this page are SOME EXAMPLES of realised measurements and principle possibilities. Further information is available at request.

**Hydraulic scale models**

The LDFM was developed for detailed flow analysis as required for DHL’s applied research and consulting activities related to e.g.:

- river bed protection
- offshore structures
- ports, breakwaters and dykes
- prediction of sedimentation

**The most important requirements can be defined as:**
- accurate measurement of instantaneous local velocities under static and dynamic flow conditions
- high stability for near-zero flow
- simple, but easy adjustable, rugged installation

Especially in the case of measurements of liquid (e.g. water) flow, methods based on hot wire and hot film techniques do not meet the requirements regarding stability.

![2-dimensional velocity measurement in waves around a part of an offshore structure model](image)

**General applications**

Although designed for applications described above, the LDFM can be used as a precision instrument for flow measurement and analysis in general, e.g.:

- laminar flow
- velocities in thin layer liquid flow
- optimisation of design of vortex and drag-force flowmeters
- dielectric liquid flow
- leak detection

Application of the LDFM is not restricted to the laboratory environment, but as long as the service conditions are met, the instrument can be a useful tool in industrial areas (e.g. pilot plants, indoor processes) as well.

**Industrial hydraulics**

![Analysis of the influence on the velocity-profile occurring behind a circular pipe-section](image)

At DHL’s industrial hydraulics calibration-, test- and research-facility the LDFM has been used for various purposes, e.g. measurements related to:

- pipe flow
- behaviour of pumps and control valves under normal and critical flow conditions
- cavitation in hydraulic circuits and machinery

The results, as illustrated below, were obtained by measuring the instantaneous velocities in a perspex pipe just behind the circular section. For turbulent flows the repeatability of the mean velocities was about 0.3%, so the mean velocity profiles could be measured with high accuracy.
L D F M Laser Doppler Flow Meter
An instrument for detailed velocity analysis

Featuring:
- 2-dimensional local velocity measurement
- non-intrusive installation
- standard range $10^{-3}$ to 2 m/s, bi-directional
- slewing rate $10^3$ m/sec²
- high static and dynamic accuracy
- 0.025% linearity
- sensed measuring area approx. 0.1 mm² (ellipsoid)

Principle of operation
Normally most liquids contain very small particles, such as solid material, bubbles etc. Incident light on these particles is partly scattered in all directions. If the particles are moving relatively to a lightsource and a detector, the frequency ($f_s$) of the scattered light has undergone a small shift with respect to the frequency ($f_i$) of the incident light. The value of the frequency-shift ($f_d$), called the Doppler-frequency, is proportional to the velocity of the particles and the angle between the directions of the incident and scattered light.

It can be shown that:
$$f_d = \frac{v (s_2 - s_1)}{\lambda} = \frac{v \cdot 2 \sin (\theta / 2)}{\lambda}$$

$\lambda$ = wavelength of incident light

Simple one plane illustration of the principle described above

The requirement for a single frequency, ultra-stable lightssource, is met by the application of a laser. Accurate measurement of the Doppler-frequency under practical flow-conditions is very complicated; details can be found in literature on this subject.* The LDFM uses the "forward scatter reference beam method" and a proven special developed "two channel tracker-counter" electronic signal processing system, enabling measurement of Doppler signals almost lost in noise while maintaining a very high slewing-rate.

* e.g.: Proceedings of the FLOMEKO-Conference, 1978.

Easy installation
The LDFM was designed for applications requiring the possibility for rapid changes in measurement set-up, without affecting the reliability of the results. The modular, but nevertheless rugged, construction has proven to permit installation and measurements by non-specialists after a very short training.

Special requirements
The most limiting factor is the need that both the liquid and the mechanical construction at the point of measurement meet the requirements regarding transmittance as mentioned in the technical specifications.

The minimum particle concentration required is available in most practical situations. If not, addition of some artificial tracer material may offer a solution.

Simplified optical diagram of the LDFM
Simplified electronic diagram for one channel

Specifications

The undermentioned specifications apply to the standard system, fitted with a 300 mm focal length front lens. Other focal length lenses are available.

1. System
   Velocity range: 10⁻³ – 2 m/sec, bidirectional in 2 dimensions.
   Repeatability: 0.5 mm/sec
   Non-linearity: <0.5 mm/sec
   Zero-stability: 0.1 mm/sK
   Slewing rate: 1000 m/s²
   Small signal response: 1 kc/s
   Sensing volume: Velocity is sensed in a volume of approx. 0.1 mm² (ellipsoid)
   Transmittance: Intensity of light received
   Particles: It is necessary that the liquid contains particles meeting some requirements regarding size and concentration, viz.: size: between 0.3 and 3 μm (diameter) concentration: vol. concentration: >1.5 x 10⁻⁶
   Power: 220 VAC, 50 - 60 c/s, 100 VA

2. Optical transmitter
   Laser: 6 mW, He-Ne (λ = 632.8 nm)
   Focal length of front lens: 300 mm, other lenses available
   Dimensions: 58 x 23 x 21 cm
   Weight: 14 kg

3. Optical receivers (two)
   Frequency range: Input 800 - 1600 kc/s
                  Output 200 - 600 kc/s
   Dimensions: 12 x 9 x 3 cm
   Weight: 0.25 kg (each)

4. Electronic signal processing unit
   Input frequency range: 200-600 kc/s
   Output: +/- 10 VDC, 2 channels
   Dimensions: 27 x 18 x 36 cm
   Weight: 13.5 kg

Options
The modular design offers possibilities for various options; e.g.:
- 1 dimensional type
- immersible transmitter/receiver
- other velocity ranges

Information about these options and other possibilities is available at request.
Appendix C

Example of an AUKE/pc SEQ-file
The AUK/E/pc SEQ-file of test #CMP01 is used here as an example and presented below. The content of the SEQ-file is in CAPITAL letters, the comments are in small lower-case letters at the right-hand side.

LOGGING
GOLVEN MET PRIMAIRE SCHOT + POSITIEVE STROOM
HOOGTE BOVEN BODEM = 0.0004 M
END:LOGGING
STO
DATATYPE,I2
ACCESS,DIRECT
FILEFORMAT,BINARY
RECL, 24

END:STO
GENERAL
PROJECT,H0840.30
START,14:33:50
STOP,14:43:50
MEASUREMENT,NAME=GOL+STRP,ID=01
SCALE, 1.00000
DATE,30-10-1992
A/D-CONVERSION,LOWSTORED=-32768,LOWUSED=-10.,
HIGHSTORED=32752,HIGHUSED=10
SCAN,RELATIONAL,HOLES
EQ,SERIES,LOW=0.0,HIGH = 599.9900,FREQ = 100.0000,
NAME = TIME,TYPE=TIME

END:GENERAL
SERIES,GHM01
ZEROLEVEL,-.191106E-03
CALIBRATION,C1 = .259120E-01,C0 = .000000E+00

DIMENSION,M
X, .105000E+02,M
Y, .500000E+00,M
Z, .560000E+00,M
END:SERIES
SERIES,GHM02
ZEROLEVEL, .144104E-03
CALIBRATION,C1 = .246300E-01,C0 = .000000E+00
DIMENSION,M
X, .165000E+02,M
Y, .500000E+00,M
Z, .560000E+00,M

begin and end of the local time during the test, sample frequency
end of section
channel nr. 1, wave gauge
zero reference value
calibration coefficients, C0 is the zero shift and C1 is the linear calibration coefficient
dimension of the measured physical values
position of the instrument
channel nr. 2, wave gauge
END: SERIES
SERIES,GHM03             channel nr. 3, wave gauge
ZEROLEVEL,.155209E-03
CALIBRATION,C1=.247900E-01,C0=.000000E+00
DIMENSION,M
X,.221500E+02,M
Y,.650000E+00,M
Z,.560000E+00,M
END: SERIES
SERIES,GHM04             channel nr. 4, wave gauge
ZEROLEVEL,.130506E-03
CALIBRATION,C1=.243900E-01,C0=.000000E+00
DIMENSION,M
X,.228500E+02,M
Y,.650000E+00,M
Z,.560000E+00,M
END: SERIES
SERIES,GHM05             channel nr. 5, wave gauge
ZEROLEVEL,.728415E-04
CALIBRATION,C1=.272700E-01,C0=.000000E+00
DIMENSION,M
X,.285000E+02,M
Y,.500000E+00,M
Z,.560000E+00,M
END: SERIES
SERIES,GHM06             channel nr. 6, wave gauge
ZEROLEVEL,-.742289E-04
CALIBRATION,C1=.246300E-01,C0=.000000E+00
DIMENSION,M
X,.345000E+02,M
Y,.500000E+00,M
Z,.560000E+00,M
END: SERIES
SERIES,SHM01             channel nr. 7, LDV flow-meter
ZEROLEVEL,-.254569E-02
CALIBRATION,C1=.912779E-01,C0=.000000E+00:

the LDV calibration factors are
not correct and have to be
corrected for e.g. cross-talk, see
Section 2.3.2 !!!

DIMENSION,M/S
X,.225000E+02,M
Y,.500000E+00,M
Z,.000400E+00,M
END: SERIES
SERIES,SHM02             channel nr. 8, LDV flow-meter
ZEROLEVEL,.333206E-02
CALIBRATION,C1=.912779E-01,C0=.000000E+00
DIMENSION,M/S
X,.225000E+02,M

Appendix C - 2
Y, .500000E+00,M
Z, .000400E+00,M
END: SERIES
SERIES,SHM03
ZEROLEVEL, .330670E-01
CALIBRATION,C1 = .912779E-01,C0 = .000000E+00
DIMENSION,M/S
X, .225000E+02,M
Y, .500000E+00,M
Z, .250400E+00,M
END: SERIES
SERIES,SHM04
ZEROLEVEL, .543989E+00
CALIBRATION,C1 = .912779E-01,C0 = .000000E+00
DIMENSION,M/S
X, .225000E+02,M
Y, .500000E+00,M
Z, .250400E+00,M
END: SERIES
SERIES,SSN01
ZEROLEVEL, -2.65726E-02
CALIBRATION,C1 = .100000E+01,C0 = .000000E+00
DIMENSION,M
X, .000000E+00,M
Y, .000000E+00,M
Z, .000000E+00,M
END: SERIES
SERIES,DBM01
ZEROLEVEL, .171510E-04
CALIBRATION,C1 = .125000E-01,C0 = .000000E+00
DIMENSION,M3/S
X, .000000E+00,M
Y, .000000E+00,M
Z, .000000E+00,M
END: SERIES
: channel nr. 9, LDV flow-meter
: channel nr. 10, LDV flow-meter
: channel nr. 11, wave-board control signal
: channel nr. 12, discharge meter
: end of SEQ-file
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