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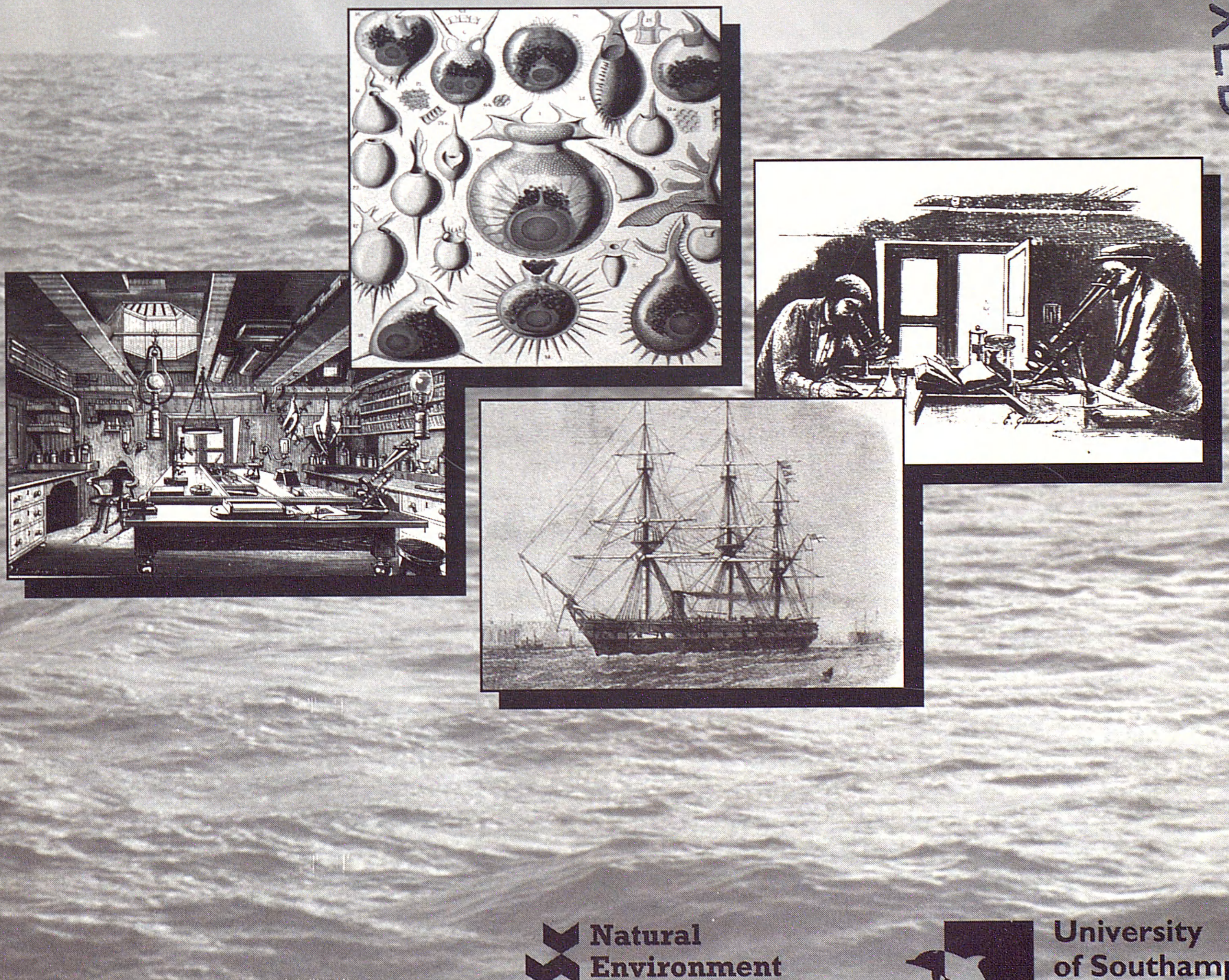
INTERNAL DOCUMENT No. 67

The 5m long recirculating flume at the School of Ocean and Earth Sciences (SOES), University of Southampton

Part I: Descriptive manual

D Paphitis & M B Collins



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ABSTRACT

The tilting recirculating 5m Recirculating Flume (Armfield), in the School of Ocean and Earth Science, Southampton Oceanography Centre, University of Southampton (UK) is used mainly for sediment transport and boundary layer flow investigations (in response to unidirectional currents (simulated) wave action or combined flows); it can be used also for any other interdisciplinary research program where adequate simulation of the near-bed flow environment is required. The flume's working channel is 5m long with a rectangular cross section (0.30m wide and 0.45m deep), an open top and glass-sided walls. Water circulation is achieved through the use of a centrifugal pump. The laboratory flume is housing a removable oscillating trolley used for simulating wave action. The operation of the oscillating trolley within a unidirectional flow produces conditions of combined wave and current flows.

The flume is equipped with a computer-controlled (DANTEC) Laser Doppler Anemometer (LDA), mounted on a high precision alignment frame, and a (Streamflo) impeller current meter. Combination of the two instruments can provide a detailed and accurate representation of the flow structure anywhere along the working section of the flume. The present report offers detailed descriptions and illustrations of all components of the flume, as well as instructions for its operation. Instructions of the operation of the associated instrumentation is also provided.

KEYWORDS

COMBINED WAVE AND CURRENT FLOWS, LABORATORY FLUME, OPEN~~C~~ CHANNEL FLOWS, OSCILLATING TROLLEY, UNIDIRECTIONAL FLOW

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Abstract

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Acknowledgements

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1. Introduction

Sedimentary processes such as sediment transport, erosion and deposition are considered to be part of physical science; hence, a clear understanding of the fluid mechanics is essential. The scientific objectives of this particular area of research have concentrated upon the response of sediments, in natural environments, to complex flow conditions. The prevailing hydrodynamics of natural environments are, however, generally, very irregular and complex. In some cases, empirical assumptions which are reasonably consistent with actual observations and experience may be made such that the conditions of flow become amenable to the analytical treatment of the theoretical associated hydraulic characteristics of such environments. A comprehensive study of the *in-situ* behaviour of flow in the natural environment requires the combination of a number of scientific instruments and personnel, to undertake such field experiments. Therefore, laboratory experiments constitute an essential component of scientific progress, since various complex aspects of the hydrodynamics/sediment dynamics of coastal environments can be simulated under controlled laboratory conditions; these can be analysed, understood and their solutions extrapolated into the field. Laboratory flumes have the capacity to simulate flows which are dynamically similar to environmental flows, permitting the detailed study of the hydrodynamics.

The 5m Recirculating Flume of the School of Ocean and Earth Science (University of Southampton), based in the Southampton Oceanography Centre, can facilitate hydrodynamical and sedimentological investigations. A wide range of flow speeds and shear stresses, typical of boundary layer flows in coastal waters, can be generated. The inclusion of the oscillating trolley enables the investigation of the hydrodynamical properties associated with oscillatory and combined (wave/current) flows. The flume is equipped with a Laser Doppler Anemometer (LDA), mounted on a high-precision alignment frame, and a Streamflo impeller current meter for flow characterisation; these are computer-controlled.

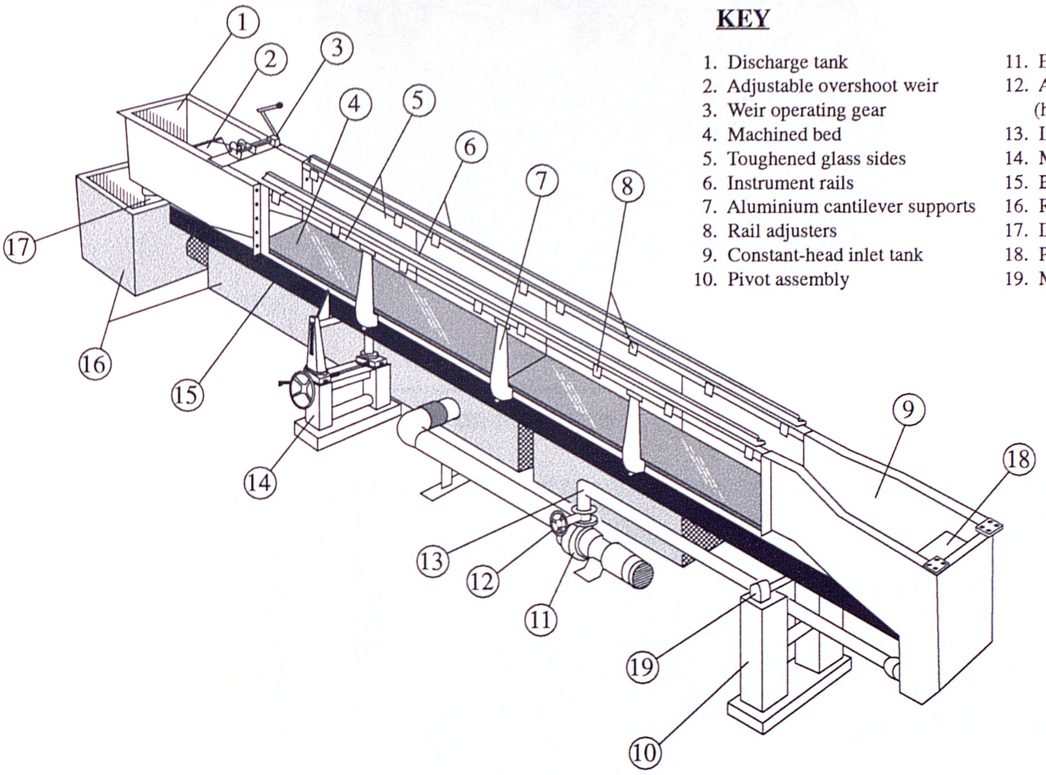
The present report (Part I) is an attempt to provide a comprehensive description of the flume facility, together with associated hardware and instrumentation, the data acquisition and processing software and guidelines for operation; it highlights their operational capabilities and limitations. The diagnostic studies into the unidirectional flow characteristics, relative to theoretical and empirical expectations, are evaluated in a companion report (Paphitis and Collins, 2001).

2. The 5m Recirculating Flume

2.1 Functional Description

The tilting recirculating 5m flume (Figure 1 and Plate 1), located in the Coastal Research Unit's laboratory at the School of Ocean and Earth Science, was supplied by Armfield Hydraulic Engineering Ltd and belongs to the S6 series. The working section of the flume is a rectangular channel, with a cross-section 30cm in width and 45cm deep. The channel (Figure 1) has an open top and toughened glass-sided walls (5), which are supported by cast aluminum cantilevers (7); the lower edge of the glass is aligned with the bottom of the channel, allowing flow measurements to be made directly above the bed. The water is pumped from the reservoir tanks (16) and, after passing through an adjustable gate valve (12), it ends up into a constant-head inlet tank (9). From there, the water flows along the channel through the working section and over an adjustable tail gate (2), into the discharge tank (1). Through a draft tube (17), the water is directed to the reservoir tank and then back into the inlet tank. The speed of the flow is controlled by the adjustable valve, which is located next to an electric pump (11) (Plate 2). The pump runs at a constant speed and pumps the (recirculating) water at up to $0.03 m^3 s^{-1}$.

In order to minimise secondary circulation and the generation of surface waves within the flume, a stilling arrangement (designed to provide a smooth transition from the turbulent flow in the inlet flow pipe (13) to a near-uniform flow in the entrance region) is incorporated into the inlet tank. As the turbulent water flow leaves the 10cm diameter inlet flow pipe it is forced to 'relax' through expansion into the much wider region of the inlet tank (approximately 50cm in width); then, it is guided straight up through this wider section, by turning through 90°. When the water reaches the level of the working section, the flow is then gravity-driven down the channel (and/or in the case of sloping beds, through the horizontal pressure gradient) and is balanced by frictional drag and inertial effects. The inlet tank contains a horizontal movable plate (18), which is forced upwards by the rising water to dampen the surface waves. An 'in-house' manufactured honeycomb-like structure, composed of 1cm tubes 8cm in length, is positioned at the mouth of the working section, to limit secondary circulation which may be introduced in the transition region; it also damps any excess turbulence, produced by the pumping action. The introduction of the honeycomb-like structure (Plate 3) was upon following after an investigation into the extent to which different techniques were damping the development of turbulence; particles of different densities were introduced into the flow, then observed visually (Paphitis and Collins, 2001).



KEY

1. Discharge tank
2. Adjustable overshoot weir
3. Weir operating gear
4. Machined bed
5. Toughened glass sides
6. Instrument rails
7. Aluminium cantilever supports
8. Rail adjusters
9. Constant-head inlet tank
10. Pivot assembly
11. Electric pump
12. Adjustable gate valve (hand operated)
13. Inlet flow pipe
14. Manual drive jack
15. Base frame
16. Reservoir tanks
17. Draft tube
18. Pivot
19. Movable Plate

Figure 1: The 5m long recirculating flume of the School of Ocean and Earth Science; generalised drawing, approximately to (relative) scale.

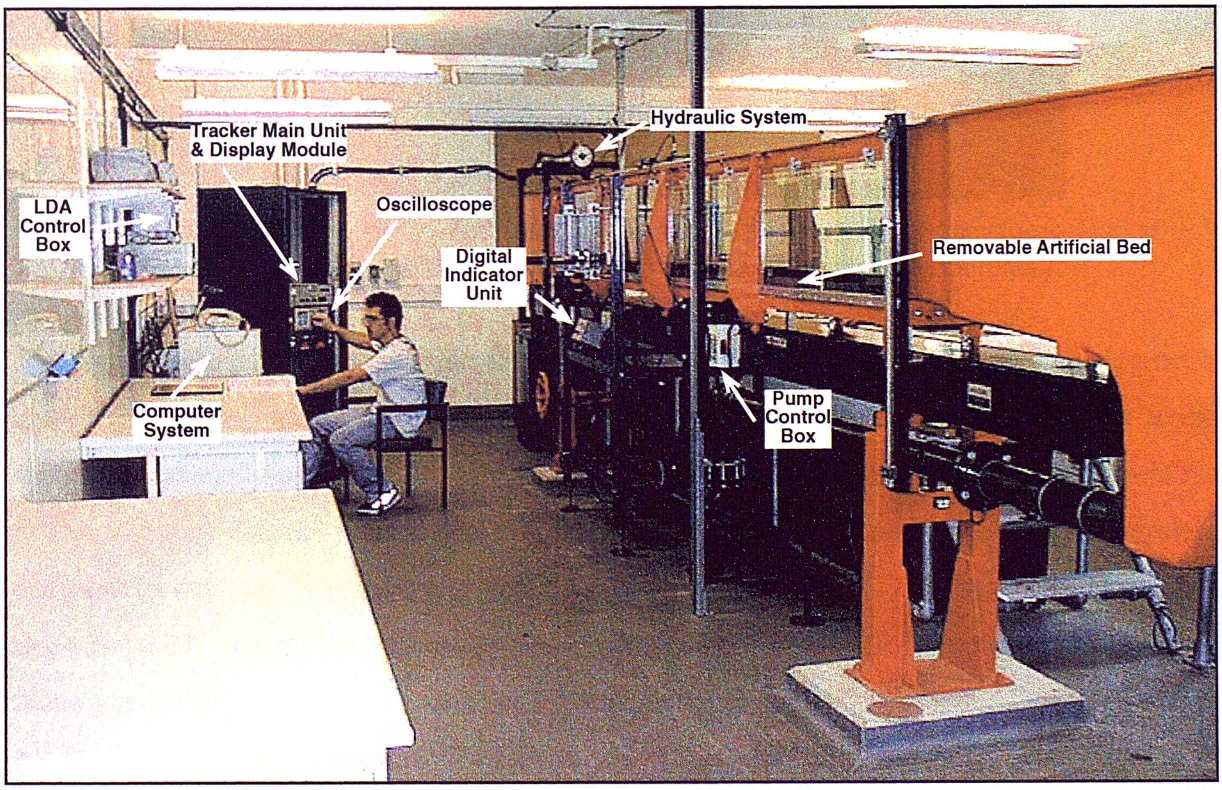


Plate 1: The general 5m flume laboratory of the School of Ocean and Earth Science.

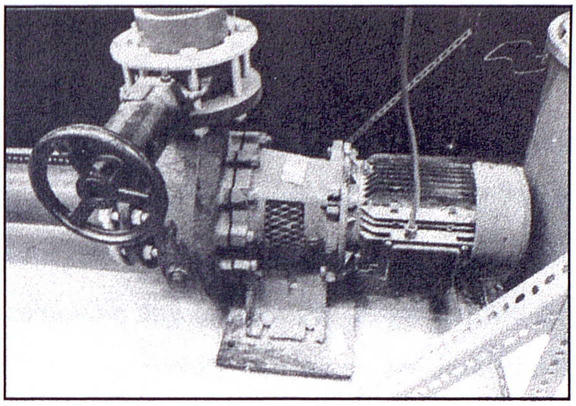


Plate 2: The electric pump, in use on the flume.

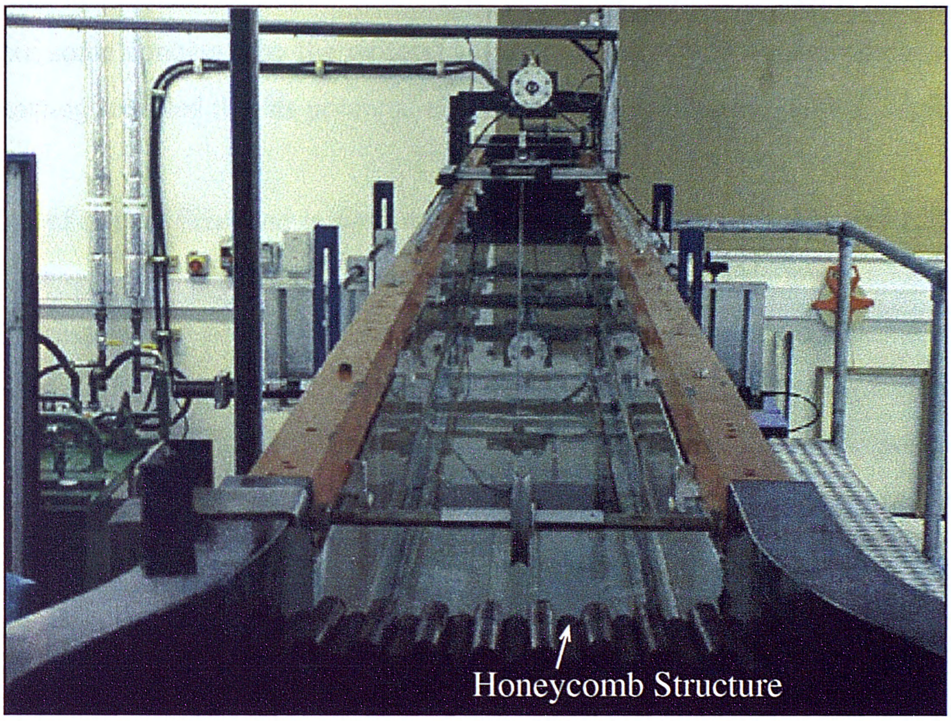


Plate 3: An upstream view of the 5m recirculating flume, showing the 'honeycomb-like' structure introduced at the entrance of the working section (to dampen turbulence).

The water depth can be set, by controlling the height of the adjustable tail gate. This downstream gate is practically watertight, so that extremely low flows can be produced in the working section. A manually-operated, screw type jacking system (14), is located at the downstream end of the working channel with a pivot at the upstream end for slope variations; the system is designed to ease the operation and precise setting of the channel. The maximum negative bed slope is ~0.25°, whilst the maximum positive bed slope is ~11.50°. At the top flanges of the flume's working section, a pair of accurately-aligned adjustable instrument rails (6) are located. An instrument carrier, which is designed to match the rails, can be placed on top of the flow channel. Positioning scales are affixed on both the instrument carrier and on one of the rails, calibrated in millimeters, to allow the level at any cross-section of the flume to be determined.

2.2 Bed Configurations

2.2.1 Removable Artificial Bed

An artificial bed was constructed of 6.5cm thick aluminium block-like structures (Figure 2(a) and Plate 1). This removable artificial bed consists of 8 individual blocks, 30cm in width by 50cm in length. Smooth aluminium plates (of variable sizes) are placed on top of the blocks and are holding them together, removing any transitional discontinuities between the blocks; depending on the experimental set-up, the blocks can be either individually covered by a 50cm long aluminium plate or jointed together with a longer plate (with a 2m plate covering up to 4 blocks). The smooth aluminium plate was selected to provide a perfectly smooth hydraulic boundary. There were some concerns (by the writers) about the relatively low-relief <1mm waviness of the bed, but testing revealed that its potential effects on shear stress were, in fact, negligible.

The design of the artificial bed is such that individual blocks can be removed and replaced with sediment, or other blocks, modified for particular experiments. This arrangement can provide a sediment recess section of variable size, in relation to its extent along the flume, with a possible (sample) depth of up to 6.5cm and located at any position from the leading edge of the working section. Sedimentary particles (forming a single grain layer), of similar composition to those in the recess section, can be easily adhered to the proceeding aluminium plates ensuring the proper development of the boundary layer.

2.2.2 Removable Plate

The aluminium plate which forms a part of the oscillating trolley apparatus (see below, Section 2.3.2) can be used as an alternative arrangement (Figure 2(b)). After placing the aluminium plate on the bottom of the flume, the sediment sample (~100g) can be placed within the recessed section (represented by a cavity positioned in the centre of the plate, in the form of a concave watchglass); this provides approximately 56cm^2 of sediment surface area. Sediment, identical to that contained within the recess, can subsequently be adhered to the plate; this consist of a layer, of a single grain thickness, which ensures the proper development of the boundary layer.

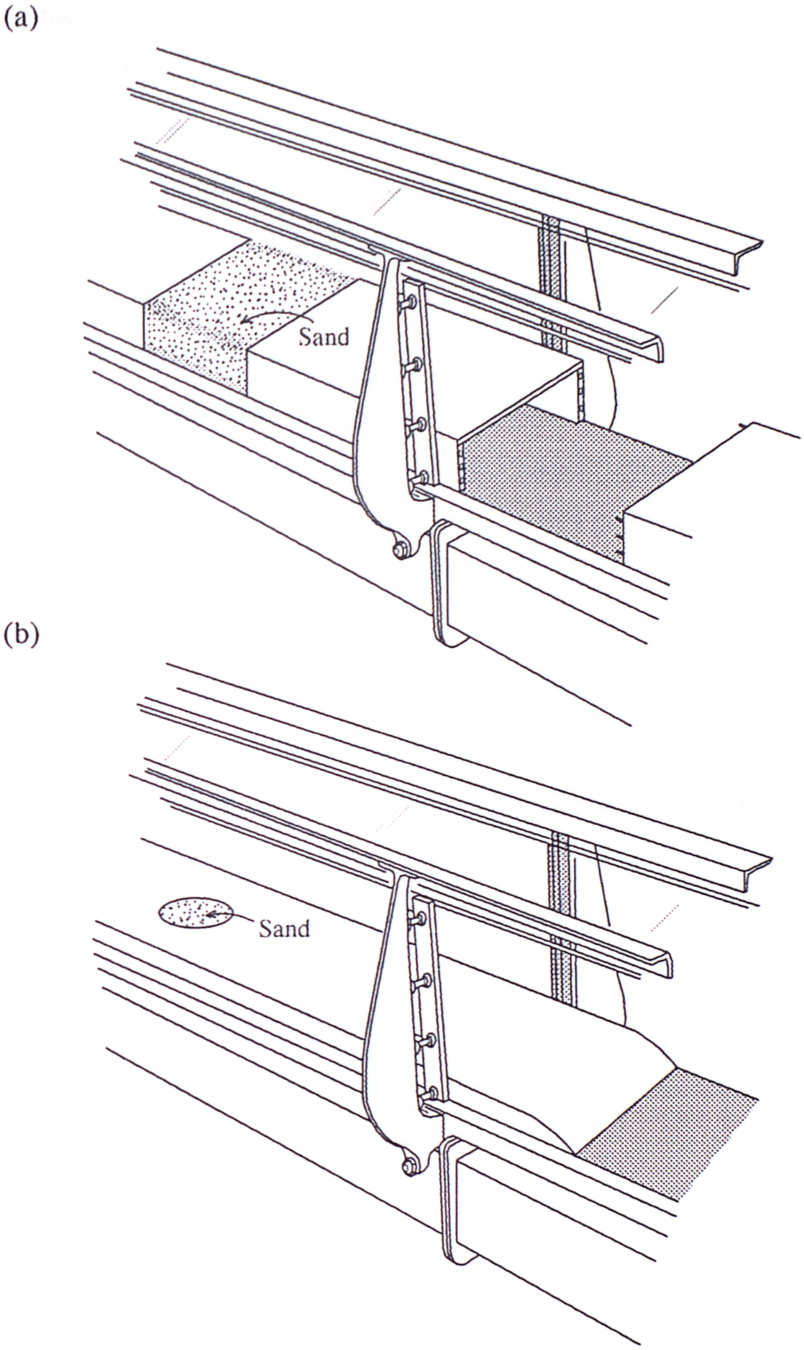


Figure 2: Bed configurations that can be used in the flume: (a) removable artificial bed, made up of aluminium block-like structure; and (b) removable aluminium plate (part of the oscillating trolley apparatus).

2.3 Oscillating Trolley

2.3.1 Operational Principle

Waves propagating in deep water result in circular orbital motions, the diameter of which decreases exponentially with depth. In shallow waters, the circular orbital motions become elliptical and increasingly narrower with depth; at the seabed, there is simply a 'to-and-fro' motion. Bagnold (1946) used this principle to introduce a new method for the study of the effect of waves on seabed sediments. According to this method, wave motion on the seabed could be simulated by the oscillation of the bed, in otherwise still water. Several investigations (Manohar, 1955; Hammond and Collins, 1979; Katori *et al.*, 1984; Panagiotopoulos *et al.*, 1994; Paphitis *et al.*, 2001) have adopted, and/or applied with modifications, this particular approach.

2.3.2 Technical Description

A cross-section of the oscillating trolley apparatus is shown in Figure 3. The oscillating plate (2cm thick, 3m long and 25cm wide aluminium plate) slides longitudinally onto the two U-shaped aluminium bars (5m long), installed on the bottom of the flume's working section (one on either side). Horizontal sliding movement relies upon stainless steel ball bearings rolling within the eight Orkot blocks, which are attached to an aluminium framework. Within each block, 10 holes were drilled into the top side, where the 1cm diameter stainless steel ball bearings are positioned (one in each hole); this is such that they protrude above the surface of the block, by 1mm. The oscillating plate rests on the ball bearings, travelling as the balls roll.

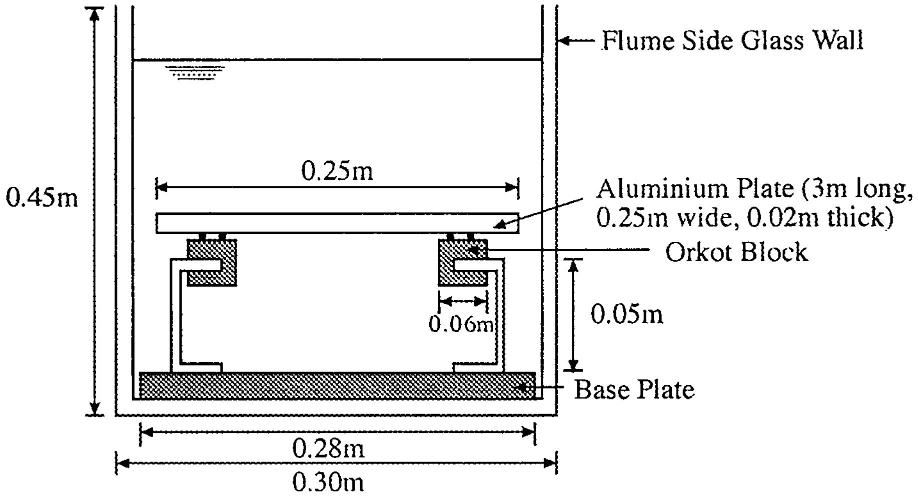
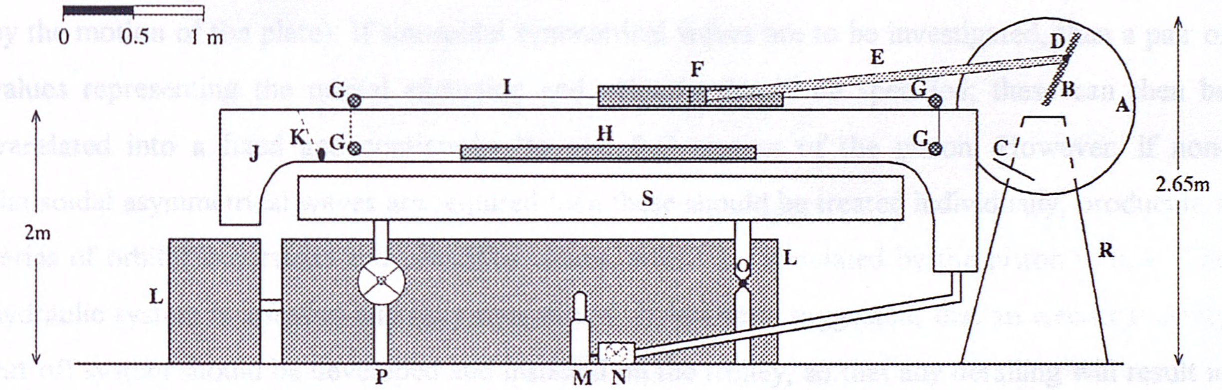


Figure 3: A cross-section of the flume, showing the oscillating trolley apparatus for sinusoidal motion.

2.3.3 Flywheel System

The trolley, placed within the bed of the flume, is caused to oscillate through an intermediate sliding mechanism. A cable-loop and pulley assembly are used to connect the oscillating plate to a connecting-rod and a cross-head assembly (Figure 4). This sliding mechanism is driven by the long connecting rod (1.82m) which is attached, by means of a pin, to one of the eight points along the radius of a rotating flywheel (Hammond and Collins, 1979). The oscillations of the plate are simulated by the rotational motion (variable radius and period) of the flywheel. The amplitude of displacement of the trolley is equal to the radial distance of the eight possible points from the flywheel centre; it can be set at the following values: 3.18, 6.37, 9.55, 14.32, 19.10, 23.90, 28.70 and 38.20cm which, in turn provide perimeters of 20, 40, 60, 90, 120, 150, 180 and 240cm, respectively. The period of rotation of the flywheel is controlled by a variable speed motor and can be varied between 3 and 20 seconds.



A - Flywheel
B - 9-position crank pin mounting strip
C - Counterweight
D - Crank pin
E - Connecting rod
F - Crosshead & slide bars
G - Pulleys
H - Trolley
I - Cable
J - Flume
K - Adjustable tail gate
L - Collector tank
O - Pivot
P - Slope adjuster
R - Stand for crank & motor
S - Supporting girder

Figure 4: The general arrangement of the 5m flume, showing the flywheel system for simulating oscillatory motion.

The motion of the trolley deviates from pure harmonic motion. Tomlinson (1993) compared the theoretical deviations of the plate to that of the flywheel, concluding that there was a small offset between the curves representing the sinusoidal and geometric plate displacement, when the oscillation periods were larger than 5s; this was observed to be greatest at the points of maximum plate displacement. The interconnection system (i.e. pulley system wires) presents a low level of slackness when the plate approaches the locations of maximum displacement, resulting in a difference between the geometric curve of the motion and the actual plate displacement (as measured by the plate positioning system). This difference is considered insignificant since, during the remainder of the cycle, the curve of actual displacement is similar with those of the sinusoidal and geometric displacements; for oscillation periods shorter than 5s, these were found to be similar throughout the entire cycle (Tomlinson, 1993). In the case of short period oscillations (5s) the plate acceleration is higher than in the case of longer period oscillations, forcing the interconnection wire to remain tauter. However, the increased inertia of the system may result in an overrun of the plate itself.

2.3.4 Hydraulic System

An hydraulic piston-type generator is connected to the oscillating plate, by means of a vertical coupling system (Figure 5 and Plate 1). Waves are generated by the reciprocating motion of the piston, which is translated directly to the plate, as a result of the straight coupling system. The piston simulates wave action through a computer software; this translates either real wave records, or selected waves, into peak orbital excursions and velocities on the seabed (represented by the motion of the plate). If sinusoidal symmetrical waves are to be investigated, then a pair of values representing the orbital excursion and velocity should be specified; these can then be translated into a fixed and continuous 'to and fro' motion of the piston. However, if non-sinusoidal asymmetrical waves are required then these should be treated individually, producing a series of orbital excursions and velocities values, which are simulated by the piston in turn. The hydraulic system is installed and fully operational. It has been suggested, that an electrical safety cut-off system should be developed and installed on the trolley, so that any derailing will result in an immediate power cut. Initial testing of its technical functionality has highlighted several problems associated with the coupling system (which connects the trolley to the hydraulic piston) as presented in Figure 5(a). An alternative solution has been suggested, which is presently under investigation, of re-designing completely the coupling system and returning to the earlier cable-loop and pulley assembly system through the necessary adaptations (Figure 5(b)). This is delivered to produce gentler trolley motion without minimal water disturbance.

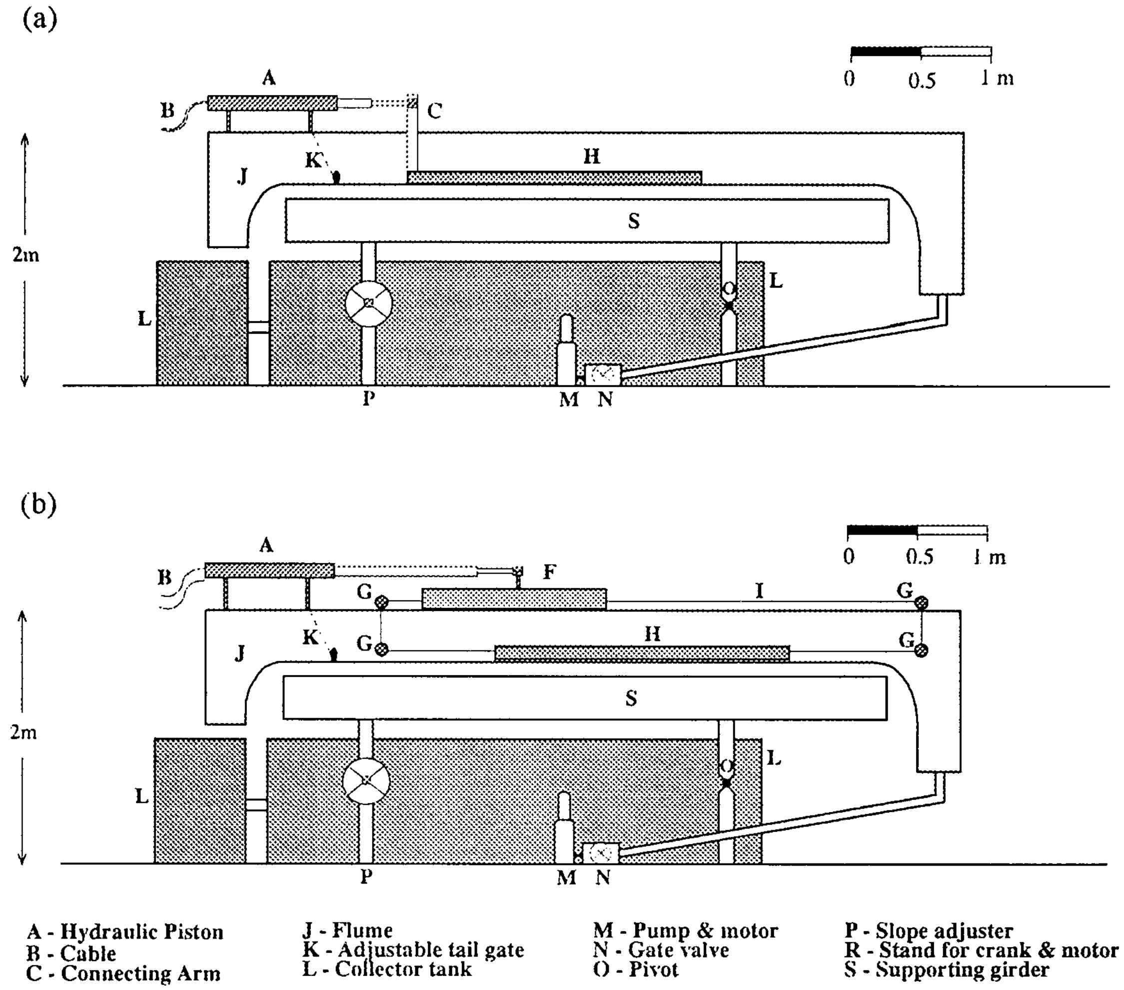


Figure 5: The general arrangement of the 5m flume, showing the hydraulic system for simulating oscillatory motion; two alternative designs: (a) coupling system; and (b) cable-loop and pulley assembly system.

2.3.5 Design Considerations

Various authors (Lhermitte, 1958 and 1960; Kalkanis,1964; Carstens *et al.*, 1969; and Davies and Wilkinson, 1977) have discussed problems arising from the simulation of waves, by an oscillating bed. The most significant of these problems are related to: (i) the introduction of inertial effects on the sedimentary grains, by the accelerating oscillating plate on which the grains rest; and (ii) the lack of a free-stream pressure gradient. However, these effects can be minimised by avoiding the conditions of short period waves combined with large wave amplitudes, as has been illustrated by Madsen and Grant (1976). These investigators showed that the ratio of inertial to drag force is negligible over a full wave cycle. Moreover, Davies and Wilkinson (1977) and Hammond and Collins (1979) have shown that if the experimental settings satisfy the condition $0.82D\sqrt{2\pi/T\nu} < 1$ (where D is the sediment diameter, T is the wave period and ν is the kinematic viscosity) then the horizontal forces are of insignificant magnitude in comparison with the gravitational forces. In such cases, the experimental results obtained from oscillating beds would be valid. Furthermore, it has been shown (Sleath, 1984 and 1991; Fredsøe and Deigaard, 1995) that the maximum bed shear stresses (relevant to the sediment threshold conditions) and the maximum bed orbital velocities (relevant to the introduced inertial forces) occur with a phase lag, ranging between 10° and 45°, depending upon the Reynolds number. Therefore, it can be suggested that although inertial forces can be introduced to the sediment grains resting on the oscillating plate, such forces may not be important at threshold conditions. The specific design has been found to suffer from a further limitation, which is the onset of resonance in the water body at certain combinations of water depth and (oscillating trolley) cycle period (Hammond and Collins, 1979).

3. Flow Measuring Devices

3.1 Laser Doppler Anemometer (LDA)

3.1.1 Operational Principle

Liquids usually contain very small particles in suspension, such as solid material, air bubbles etc.; light incident on these is partly scattered, in all directions. If the particles are moving, relative to a light source and a detector, the frequency of the received scattered light would have undergone a small shift, with respect to the frequency of the incident, originally-transmitted, light. The value of the frequency shift (the Doppler frequency) is proportional to the velocity of the particles; thus, of the flow. This interpretation is based upon the assumption that such particles of fine-grained detritus, contained within the flow, travel at the same speed as the ambient flow itself. In order to measure these relatively small frequency shifts, it is necessary to use two (light) beams with a high degree of coherence in space and time. In practice, this is achieved by using two beams originating from the same source, with there axis intersecting at a single point. The volume that the beams have in common forms the measuring volume.

3.1.2 Technical Description

The Laser Doppler Anemometer (LDA) (supplied by DANTEC, Bristol) emits a 5mW helium-neon laser beam (Figure 6(a) and Plate 4 and 5). After emission, the laser beam enters an optical unit, called beam splitter, where it is split into two beams; these are polarised into mutually-perpendicular directions and, by means of a beam displacer travel out of the optical unit, as two parallel beams. Passing through a convex lens, these beams are made to intersect at a point equal to the focal length of the lens, where the velocity measurements are made. The region within the flow, from which Doppler signals are received and detected by the diode detector, is defined as the Measuring Volume (MV) (Figure 6(b)). Some of the light entering the MV is scattered away by the fine-grained particles contained within the flow, causing a frequency shift with respect to the originally transmitted light. A diode detector (aligned carefully to receive the reference beam) observes the two light signals: one with the frequency of the incident light (F_i), and the other with a frequency shift arriving at the detector, after being scattered from the particles (F_s). This coaxial arrangement, between the diode detector and the reference beam, ensures that only light passing through the MV is detected. Any other light travelling towards the diode detector will not be seen, as it will be at a greater angle. The value of the frequency shift (Doppler frequency) F_D (= F_s - F_i) is determined by the detector. Subsequently, a Doppler Frequency Tracker receives the

F_D signal and produces an analogue or digital output signal, proportional to the velocity of the particles and, hence, to the speed of the flow. The Doppler frequency (F_D) is related to the speed of the ambient flow (U), through

$$F_D = KU \tag{1}$$

where $K=\lambda/2\sin(\theta/2)$. In this expression, θ is the angle between the incident and scattered beams and λ is the wavelength of the incident light (Figure6(b)). For the geometry which is used presently, $\theta/2=4.289°$ and $\lambda=6.33\times10^{-5}$cm, whilst K equates to 0.4232cm s^{-1} kHz $^{-1}$. The final equation relating the speed of the flow (U) to the Doppler frequency (F_D) is

$$U = 0.4232 \times F_D \tag{2}$$

When the Doppler frequency (F_D) is registered by the diode detector, it is transmitted to the Doppler Frequency Tracker (DFT). A simplified block diagram of the DFT is shown in Figure 7, illustrating the series of events which take place. The weak Doppler signal is first amplified, then filtered. This amplified input signal is forced by the lock detector to lead the sinusoidal signal produced by the Voltage Control Oscillator (VCO), by 90°. A scanning procedure follows, to determine whether the two signals match. If a match is detected (where the two signals are equal), then the system is locked. The matching frequency is converted into voltage, by passing through the frequency/voltage converter; it is then sent to a 'sample and hold' device and, subsequently, to an analogue output socket. When the analogue signal is registered, the system is out of lock and the scanning at the selected frequencies, until another match is detected.

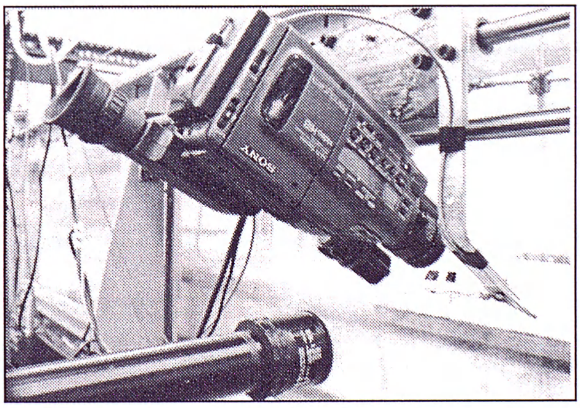


Plate 4: The transmitting unit of the LDA and the video camera.

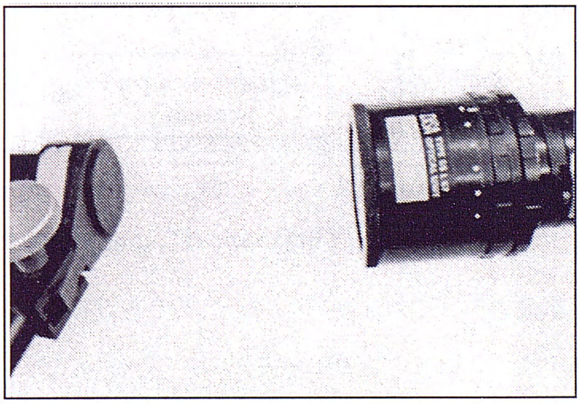


Plate 5: The head of the transmitting unit and the diode detector of the LDA.

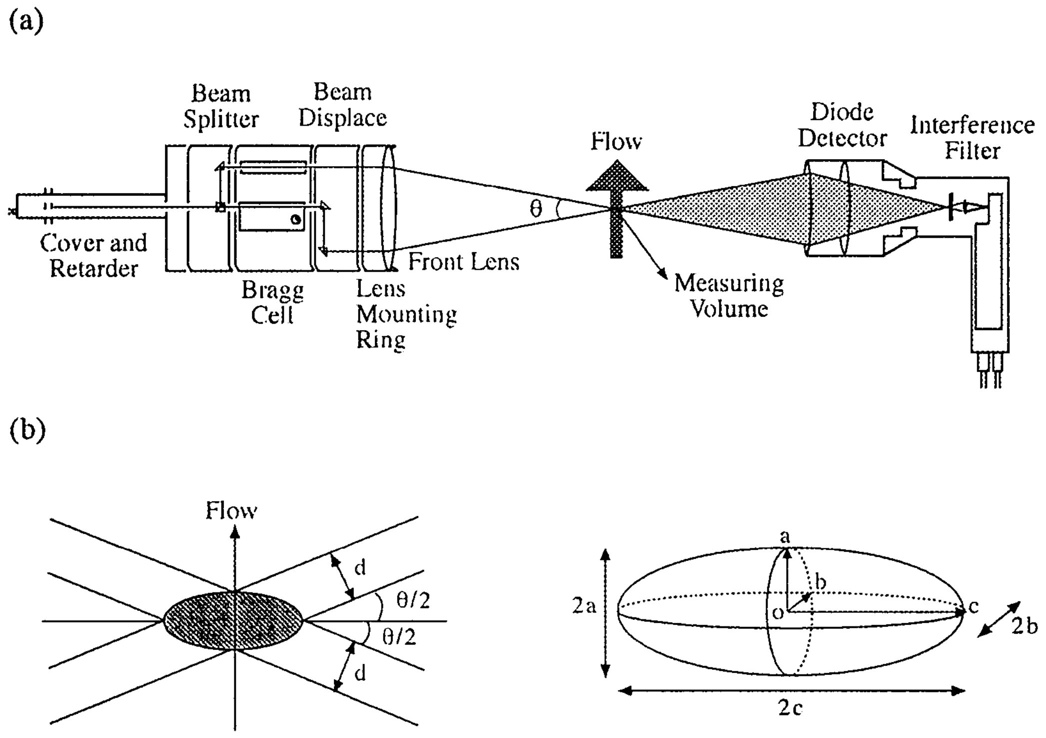


Figure 6: (a) Laser Doppler Anemometer operated in the forward scatter differential mode; the transmitting unit is shown on the left and the receiving unit (diode detector) on the right, of the Figure. (b) Schematic view of the beam geometry and Measuring Volume. Using a beam separation of 45mm and a convex lens of 300mm focal length, with the beam diameter taken as 0.800mm, the dimensions of the Measuring Volume are a,b=0.4mm and c=5.348mm.

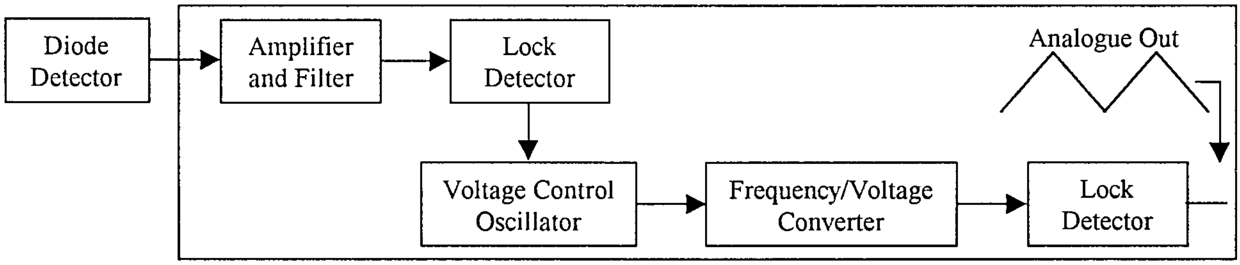


Figure 7: Simplified block diagram of the Doppler Frequency Tracker (DFT).

3.1.3 Spatial and Temporal Resolution

The finite extension of the measuring volume (in the downstream direction, having a scale of 0.4mm) results in a spatial integration of the flow field (the velocities of several particles are averaged, at any given time). LDA measurements obtained with continuous Doppler signals are affected by Doppler ambiguity noise; this is caused by the random dispersion of the particles in the flow and the resulting random phase composition of the scattered light. In the present study, the system was found to be incapable of measuring flow velocities of less than $0.5cms^{-1}$. Having a geometric arrangement of only two beams, the system is also incapable to distinguish positive and negative velocities and, hence, flow direction.

The temporal response of the laser system depend upon the coherent or residence time of the detected signal, which is the time it takes a particle to traverse the measuring volume (inertia of the particle); thus, it is the time available for detecting the frequency of the Doppler signal. With the wavelength of the laser being of the order of the size of the particles in suspension, the errors are minimised; in addition, accurate low-pass and high-pass filters are used. For example, in cases where the selected frequency range is retained at 10-100kHz, the resultant instrumental error is of the order of $\pm 0.2cms^{-1}$; thus, the systems accuracy is ±0.2%.

Despite its physical dimensions, the LDA has several advantages as a flow measuring device. The instrument is located outside the flume, causing no disturbance to the flow; hence, it could be positioned within the boundary layer, close to the sediment bed and to an accuracy of ±0.1.5mm. The instrument offers high-frequency response to instantaneous velocity changes (>1000 Hz).

3.1.4 System Calibration

Using a frequency-generator unit, a series of known frequency signals were introduced into the LDA system. Such an approach provided a procedure for testing the analogue device, as well as the direct velocity display. Ten different frequencies were applied to the unit and the corresponding analogue output signal was analysed, subsequently, by the computer. The tracker main unit through the use of the calibration factor (see above) displayed the theoretical (anticipated) velocities. The corresponding analogue output calculations of velocity, obtained from the known input-frequency signal, were found to be fractionally higher than the anticipated velocities. The differences were found to be in the range of ±0.01 to ±0.02cm/s; these have been assumed, therefore, to be insignificant.

3.2 Streamflo Current Meter

3.2.1 Technical Description

The Streamflo miniature impeller current meters used was designed for measuring low flow velocities (of between 2.5 and 150cm/s) of conducting fluids (Figure 8 and Plate 6). When the measuring head of the meter is immersed into flowing water, the rotor is forced to rotate at a rate proportional to the flow velocity. The passage of each blade (constructed of a material with an impedance differing to that of water), past gold wire tip at the end of the tube, causes a measurable change in the 'impedance' between the tip and the tube. This variation is used to modulate a 15kHz carrier signal, which is then amplified and filtered, to produce a square wave signal. The pulses of this signal are integrated over a specific period of time, to provide a digital reading (DC voltage) proportional to the flow velocity.

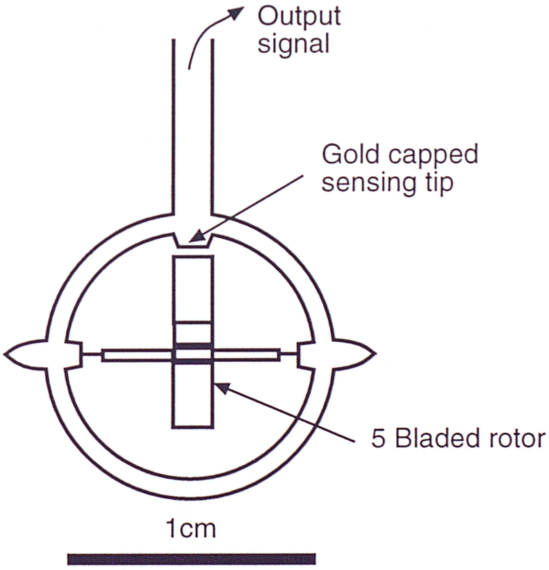


Figure 8: Measuring head of the Streamflo miniature impeller current meter.

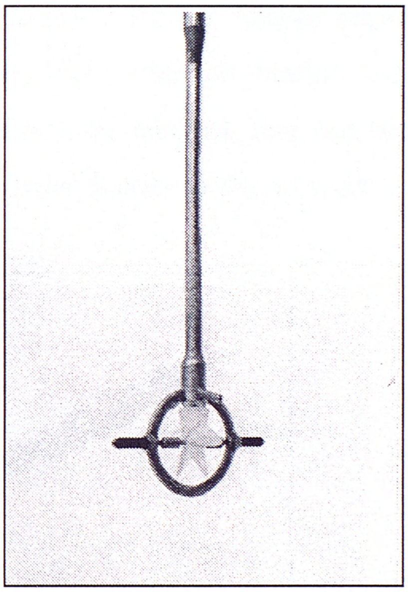


Plate 6: The Streamflo impeller current meter (for scale, see Figure 8).

3.2.2 System Calibration

The meter provides an analogue output, or a digital indication of rotor frequency (in Hz), with high-velocity measurements being accomplished by means of an alternative range; in this the true frequency is approximately 5 times the indicated frequency. The analogue signal is corrupted by a variable saw-tooth wave-form, due to individual pulses as each rotor blade passes the gold sensor. Measurement of the time interval between each successive passage of the rotor blades would provide a measure of the fluid velocity in laminar flows.

Turbulent flows produce, however, superimposed low frequencies on the rotor pulses. Electrical noise will also produce high-frequency fluctuations in the signal. Consequently, a series of Streamflo calibrations were undertaken using the LDA (see Section 3.1) and over a variety of flows. The Streamflo was positioned immediately behind the measuring volume of the laser (assuming that both systems were measuring at the some position). A linear formulae relating Streamflo output voltage (V) to flow velocity (U) (as measured by the LDA, within the 3-33kHz) frequency range), was obtained using a least squares regression

$$U=4.679V+3.067 \qquad (3)$$

This expression giving a correlation coefficient of 0.986 (with a p-value of <0.000 at the 99% level of significance, suggesting a very strong relationship). This derived calibration curve is illustrated in Figure 9. The analogue output signal was found to have a delayed response time, taking up to 1s for the signal to reduce to a zero-velocity level, after the rotation had stopped. Over-running of the rotor, due to inertia, was found also to be minimal; this was because the material with which the blades were constructed was of similar density to that of water.

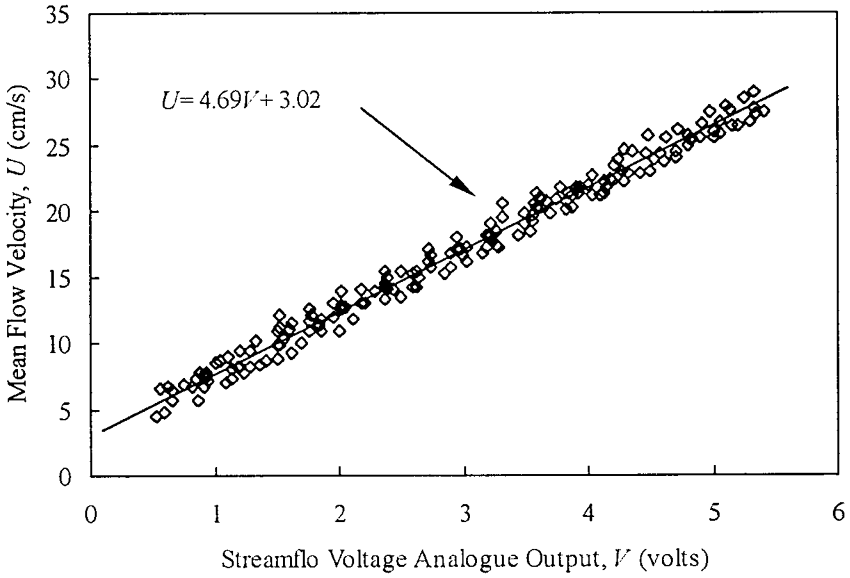


Figure 9: Calibration curve of the Streamflo current meter, using the flow velocities as measured by the LDA system.

3.2.3 System Limitations

The impeller current meter is one that has to be manually oriented into the flow; hence, extreme care is required in this procedure, as it may lead to discrepancies in the flow velocity measurements. The Streamflo is subject to 'fouling' (by particulate/organic matter), which is a common limitation with all such impeller current meters and, as with the LDA, it provides no indication of flow direction. Further, the meter creates an obstruction to the flow, giving rise to additional turbulent eddies; hence, in cases where this is to be used in conjunction with the LDA, it must always be positioned above or downstream from the LDA Measuring Volume and away from the sediment/water interface being studied (Paphitis and Collins, 2001). As this particular Streamflo is mounted at the top of the flume, relatively high flow rates were found to set up some (but essentially minimal vibrations), producing additional noise An aluminium bar was designed which can be introduced just above the water surface, on the upstream side of the Streamflo (acting as an additional support mechanism); this was found to minimise the vibrating noise, to insignificant levels (<0.1%).

4. Data Acquisition and Analysis Equipment

4.1 Computer System

The cycle of data generation was not complete until these were converted into a digital format, which can be processed and analysed; hence, the final stage of the cycle is their registration onto the computer. In order to achieve this objective, the voltages generated by the LDA and Streamflo units are sent to the computer (Plate 1), equipped with a data acquisition (A/D) card; this consisted of 16 single-ended analogue input channels (with the analogue input range switched to ±5volts DC), via a data-logging device (the LDA had a voltage divider).

4.2 Processing Software

The computer software developed for the flume can be used to provide, at any particular moment, real-time displays on the screen of the horizontal component of the flow velocity, from both the LDA and Streamflo unit. The system can process and integrate the signals from six sensors at any one time, at different frequencies. This software is logging the data using a digital quanta range of 0 to 4096 bits, which correspond to the 0 and 5 volts level, respectively. Generating known voltages from a voltmeter, with the exact voltage being finely-tuned by means of an adjustable power unit, a series of digital values (number of bits) were recorded. An algebraic expression was derived relating the two variables, such that

$$V = (B - 2048) / 409.6 \tag{1}$$

where V is the voltage analogue output and B is the digital output. The Streamflo voltages can be converted to flow velocity measurements directly using Eq. 3. For the LDA, because of the voltage divider introduced into the logging device, the calculated voltage needs to be multiplied by a factor of two. The Doppler frequency (F_D), derived from the LDA, can be calculated using

$$F_D = 0.1(V\,R) \tag{1}$$

where R is the maximum frequency in the selected frequency range, on the tracker main unit of the LDA system, and the unit of the constant (0.1) is volts. F_D must then be multiplied by the calibration constant (K=0.4232), to provide the flow velocity.

4.3 Miscellaneous Equipment

4.3.1 Video-Monitoring Equipment

A Sony CCD-V800 Hi8 portable video camera (Plate 4), used in conjunction with a Sony PVM-1444QM monitor, can be used to observe and record sediment movement (e.g. during threshold investigations) and flow particle tracking (e.g. flow visualisation). The camera is selected specifically for its 'time-code' function, which effectively marks the visual record every 0.04 of a second. Since the video camera is filming at this frequency, it is beneficial that the LDA and Streamflo current meters are also set to sample at 25Hz. The events can be recorded by a Video Recorder (Sony 4430E), with 'freeze-frame' and 'frame-advance' facilities.

4.3.2 Ultraviolet Spotlight

An Ultra Violet (UV) spotlight (supplied by RSL Ltd) can be used to illuminate fluorescent sediment grains contained within the sample (Plate 7). The UV spotlight, if required during an experiment, can be fixed in a pivotable clamp above the sediment recess, allowing the pathway of the grains along the bed to be identified and followed easily.

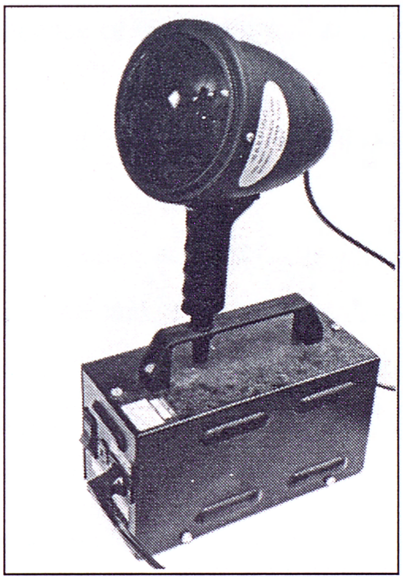


Plate 7: The ultraviolet spotlight, for use with fluorescent grains.

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Appendix: User's Guide to Operations

A.1 The 5m Recirculating Flume

A.1.1 Fill-Up Procedure

Prior to filling the flume, it should be established that the reservoir tanks are clear of any objects that may cause damage to the pump during operations; similarly, that the draft tubes connecting the reservoir tanks are water tight. The filling operation should be supervised (at all times) by the sediment dynamics technician (John Davis), to avoid any flooding of the flume laboratory. The reservoir tanks should only be filled up to three quarters of their capacity; to such a depth, this requires approximately 4 hours.

A.1.2 Flume Operation Checklist

Step One: The mains isolator must be switched on, to activate the power supply to the flume.

Step Two: Ensure that the hand operated flow control valve is closed.

Step Three: Check that there is nothing within the working section that could be swept into the reservoir tanks; small objects could make their way through the system, damaging the pump.

Step Four: Select the slope of the flume, for the specific experimental run.

Step Five: Start the electric pump, using the green button on the pump control box (Plate 1).

Step Six: Open (incrementally) the hand-operated flow control valve, to establish the flow of water through the working section.

Step Seven: When the desired flow velocity is achieved, raise the adjustable overshoot weir to the required level to achieve the desired water depth; this is an iterative procedure.

Step Eight: When completing an experimental run, the flow control valve should be closed whilst the pump is still running.

Step Nine: Switch off the electric pump (using the red button on the pump control box) and the mains isolator.

Step Ten: Return the flume slope to zero, after all the water has drained from the working section.

Step Eleven: If the water has become dirty (e.g. during a tracer study, or when dense particles for flow visualisation are used, etc.), then draining of the flume is required. The draining valve is located on the side of the first reservoir tank. A hose should be used, to avoid flooding the laboratory.

A.2 LDA Operation

A.2.1 Cautionary Note

The LDA is a delicate instrument and if not treated with respect, it can cause damage to an individual. The system operates with a Class B laser beam, which does not harm the skin but can cause serious damage to the eyes. Hence, it is important to maintain the filter on, when aligning the receiving and transmitting optics. It should be noted that the side panels must be maintained free of scratches, as these can cause refraction of the laser beam; this will not only provide a false signal, but can also be hazardous to the operator.

A.2.2 LDA Operation Checklist

Step One: Connect the extension cord from the diode detector, to the logging device.

Step Two: The laser control box (Plate 1) must be switched on, to activate the power supply to the LDA.

Step Three: Switch on the computer, frequency tracker and oscilloscope.

Step Four: The (yellow) reset button on the control box must be pressed, prior to turning the key for switching on the system.

Step Five: The safety circuit, which causes an immediate power shut-down if the door to the laboratory is opened, should be checked prior to operating the system. Once the key is turned, the door should be opened to check that the safety circuit is working properly. The system can then be reset and switched on again. Once an experimental run is underway, the laboratory should not be left unattended. However, if for any reason the operator needs to leave the laboratory for a short period of (time but without interrupting the data logging), the safety circuit can be disabled for a 10 second time window; this permits the door to be opened and closed before engaging again. From the inside, there is a button located on the left side of the door; from the outside, a four-digit security code must be used; this can be obtained from the Principal Scientist responsible for the flume laboratory, or the sediment dynamics technician.

Step Six: Open the shutter of the laser gun (transmitting unit) and, without removing the filter, align the (receiving and transmitting) units together using the left-side beam. The alignment can be performed with ease, without being hazardous to the operator, thanks to the parallel mounting system.

Step Seven: When alignment is achieved, then the filter should be removed and the signal, appearing on the oscilloscope (Plate 1) must be checked. The oscilloscope permits visual examination of the received signal; its controls can be set to fit the operator's preferences (e.g. select Channel 1 and set Volts/Dive to 0.1v/Div and Timebase 2ms).

Note: The diode detector must be rotated slowly so that the best signal can be found; this is where clear bursts from individual particles, passing through the illuminated area (e.g. Measuring Volume), can be observed (Plate 8).

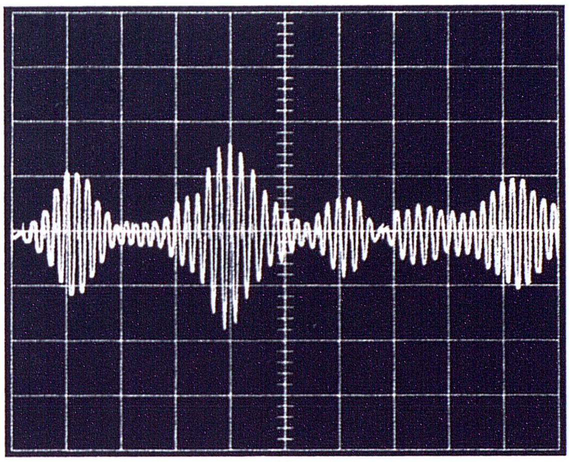


Plate 8: An idealised particle signal showing the bursts from individual particles passing through the illuminated area of the Measuring Volume.

Step Eight: When a good quality signal reception is achieved, the controls of the Doppler Frequency Tracker must be set. The controls and their functions of the tracker's main unit and display module are explained below (the numbering relates to the labels shown on Figure 10, see also Plate 1):

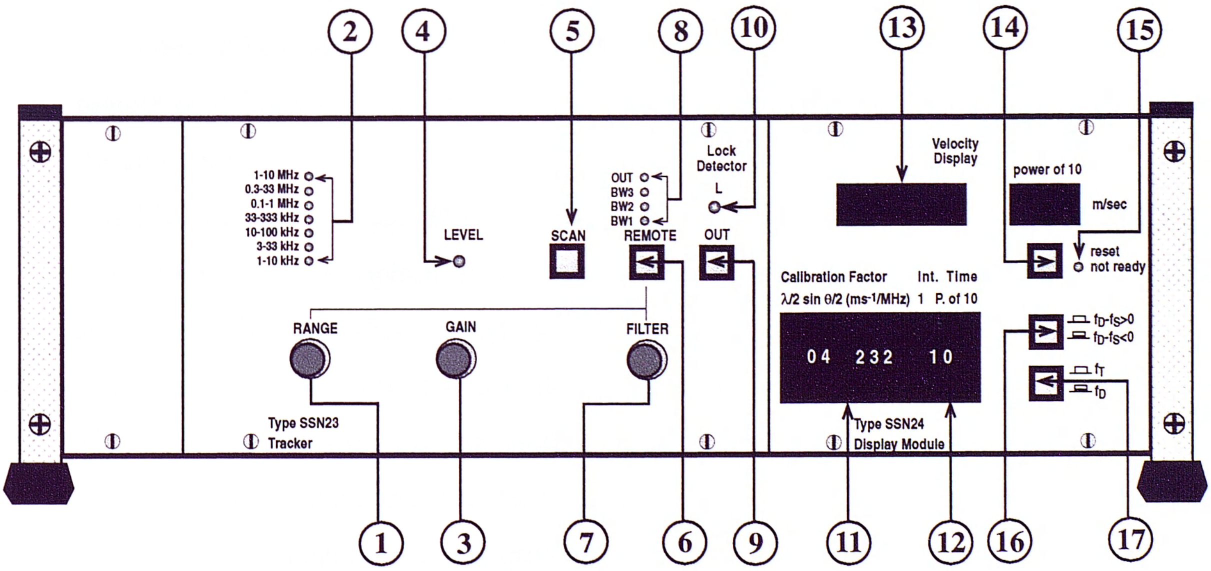


Figure 10: The tracker main unit and display module of the LDA system.

Tracker Main Unit

1. The RANGE selector knob is used to select between the seven tracking ranges; the selection depends upon the experiment requirements, in terms of velocity range (minimum and maximum).

RANGE	VELOCITY RANGE
1-10kHz	0.42-4.23cm/s
3-33kHz	1.27-13.97cm/s
10-100kHz	4.23-42.32cm/s
33-333kHz	13.97-140.93cm/s
0.1-1MHz	0.42-4.32m/s
0.3-3.3MHz	1.27-13.97m/s
1-10MHz	4.23-42.32m/s

   Note: The MHz ranges are only an approximation, as the flume can only generate (with an horizontal slope) flows within the safety limit of about 2m/s.
2. The Range display is indicating, by a light, the selected frequency range.
3. The GAIN adjustment knob is used to set the right gain level.
4. The LEVEL indicator flashes (just) when the gain knob is properly adjusted.
5. The SCAN push-button can be used to scan the frequency ranges, to identify which one is most appropriate for the specific flow conditions. When depressed (on), the tracker will operate as a spectrum analyser. If the frequency range is known or identified, the scan push-button should be released.
6. The REMOTE push-button can be use in cases where the tracker is connected to a computer. When depressed (on), the tracker ranges and filters are remotely-controlled. The remote push-button should remain released as the tracker cannot be controlled remotely be the computer.
7. The FILTER selector can be used to smooth out noise fluctuations present in the signal. The operator has the option of not using a filter (OUT), or inserting a filter of increasing smoothing effect (low-pass to high-pass filters), by going from BW 3 to BW 1.
8. The filter indication shows the filter function inserted in the analogue output signal.
9. The OUT push-button can be used to disable the out-of-lock detection circuit. It is beneficial to maintain the out push-button released (off), otherwise the lock detector indicator will remain inoperable, providing no indication as to whether the system is in- or out-of-lock.

10. The LOCK DETECTOR indicator shows a green light, when the tracker is in lock.

Display Module

11. The CALIBRATION FACTOR thumbwheel is used for programming the correct calibration factor, from the LDA's optics geometric arrangement; this is currently set at 0.4232 (with units of cm s^{-1} kHz^{-1}).
12. The INT. TIME (integration time) thumbwheels are used for settling the integration time, for the mean velocity calculations.
13. The VELOCITY DISPLAY shows a real-time digital display of the mean velocity (m/s).
14. The RESET push-button is used for resetting the velocity display (e.g. when the int. time is changed).
15. The NOT READY indicator lights show when the time used for averaging has not reached the integration time selected.
16. The f_D-f_S>0/ f_D-f_S<0 push-button plays an important part in the velocity measurements featuring frequency shift with respect to the velocity sign selection. In the present arrangement the Doppler Frequency Tracker is not used in conjunction with a Frequency Shifter. Hence, this push-button should remain depressed (f_D-f_S>0).
17. The f_T/f_D push-button when depressed, is for simple measurements of the tracker input frequency (no shift). The button should be released when the Doppler Frequency Tracker is operating, in conjunction with a Frequency Shifter. For the present arrangement where the tracker is used as a 'stand-alone' unit, the push-button should be depressed (f_T) at all times.

A.3 Streamflo Operation

A.3.1 General Note

The Streamflo probes are delicate laboratory instruments; hence, extreme care should be taken when handling them during mounting. The probe must be secured onto the movable mounting system, attached to the rails, found above the working section of the flume and carefully aligned to the flow.

A.3.2 Streamflo Operation Checklist

Step One: Align the probe carefully, to the flow direction.

Step Two: Connect the digital indicator unit (Plate 1) to a suitable mains supply, in accordance with the voltage stamped on the rear panel.

Step Three: Connect the probe to the digital indicator; switch on the unit and select the desired frequency range.

Step Four: Connect the digital indicator to the logging device, so that the data are logged directly onto the computer.

Step Five: At the end of the series of experiments, the probe should be rinsed with distilled water and placed carefully back into the instrument case.

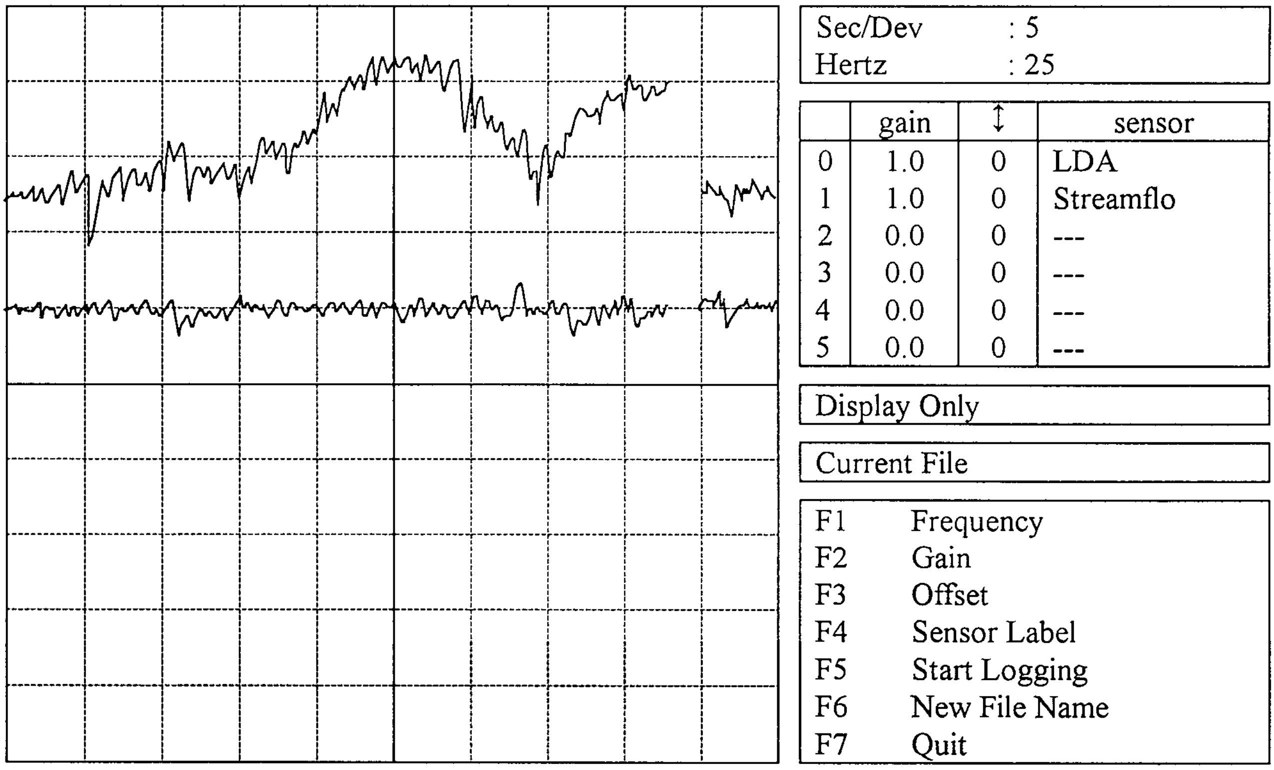
A.4 Processing Software

A.4.1 General Note

Prior to the beginning of each series of experiments, the operator should create a new directory within which to store the generated data files. All the files must be backed up at the end of each day. The operator's directory will be maintained for a three month period, following the end of the experiments; after this time, it will be removed by the Principle Scientist or the sediment dynamics technician.

A.4.2 Main Menu

The main menu appears upon entering the software; this permits easy alteration of the data acquisition requirements, as well as displaying the real-time results onto the screen (Figure 11). Up to six sensors can be integrated at any one time; these can be labelled and distinguished, on the basis of colour. The software can operate under two modes, namely, display only and logging mode. For the logging mode to operate, a file name must be specified; once the name is entered, it will appear in the current file space on the screen; the display screen will remain on hold, indicating that the system is ready to write data on to that file. Once everything is set up, the function key (F5) can be pressed so that the system can commence logging. The operator can also change with ease the frequency, gain and offset (↕) using the designated F-keys.



Sec/Dev : 5
Hertz : 25

	gain	↕	sensor
0	1.0	0	LDA
1	1.0	0	Streamflo
2	0.0	0	---
3	0.0	0	---
4	0.0	0	---
5	0.0	0	---

Display Only

Current File

Figure 11: The main menu of the processing software, located on the laboratory computer.

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