A Scalar Concentration (Komori) Probe for Measuring Fluctuating Dye Concentration in Water

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Abstract: - The scalar (dye) concentration probe of Komori has been used at QUT to measure the mixing and dispersion of pollutants in rivers from outboard motors and in a gross pollutant trap (GPT). Although usages have been documented in literature, little is known of the Komori (dye) probe's frequency response characteristics and the quality of data sampled. In this work, the frequency response characteristic of the Komori probe is determined by injecting methylene blue dye over a range of water flow velocities. Despite some noise and drift, the data collected from the probe is useful because of its high frequency response in comparison to regular commercial concentration probes. The rise and fall times are reported and the theoretical response time is also determined. It is found that the frequency response is a strong function of flow velocity and a maximum of 100 Hz is noted under typical operating conditions. Comparison between rise and fall data show that the rise time is generally shorter than half the fall time.

Key-Words: - Concentration probe, dye measurement, frequency response, Komori probe, tracer, rise time and fall time

1 Introduction

Tracer experiments are useful to study the flow characteristics in fluid systems. Examples of such systems are chemical reactors, processing equipment, stormwater quality improvement devices (ponds, wetlands, pollutant traps), biological systems, porous aquifers, groundwater flow, separators, mixing and dispersion of pollutants in open waters.

Tracer experiments are performed by injecting a tracer into the incoming fluid, and to continuously (as function of time) monitor the tracer concentrations at the system outlet. The time series data can then be used to measure the residence time distribution (RTD) and the average time it takes the fluid to pass through the system boundaries [13]. Also from the data, the average stream velocity can be estimated [26]. The RTD is a useful tool to analyse the flow and mixing process in a system. This information can then be used to develop and validate analytical or empirical models [13].

A review of recent tracer methods is given [22]. Although the paper is intended for applications in unconsolidated porous media, it does provide useful experimental background information. Tracer experiments carried out in wastewater treatment plants are studied [9, 10]. A list of tracers used for laboratory and field experiments and implications of their usage are also given [10, 22]. Common tracers are salts, fluorescent dyes and fluoride. For RTD studies of wastewater treatment plants [9] and ponds, wetlands and detention tanks

[1, 14], the usage of fluorescent dye (rhodamine WT) with portable field analysers (a flow through fluorometer by Turner Designs) have been reported. The same tracer was used to measure the mixing transport coefficients in natural channels [5]. Salt based tracers such as lithium chloride have been deployed to measure the RTD of a model hydrodynamic vortex separator [2]. In the hydraulic testing of a wetland, bromide was given preference to rhodamine WT [18]. In both cases, the fluid samples had to be collected, stored (also termed grab sampling) and analysed. Lithium chloride was analysed with an absorption spectrophotometer and ion chromatography was used to detect bromide concentrations. In rapid changing flow conditions or where high frequency sampling is required, the grab sampling technique is not suitable. Tracer tests carried out in water distribution networks with other salt based tracers such as sodium chloride, calcium chloride and fluoride are reported [4, 21]. In this case, the tracer concentrations were measured continuously with conductivity meters.

To study turbulent mixing between two species and to perform measurements of dye concentration fluctuations in reacting flows, [12] found it necessary to use custom built scalar (dye) concentration probes (manufactured by Masatoyo P/L, Japan). Unlike some tracer methods, the custom probes are capable of sampling data at high frequencies over several channels. This increases the measurement resolutions in complex flows and enables real time data comparison between the inlet

and outlet probes. The geometrically slender construction of the probe provides an additional feature in that a number of probes can be deployed within confined areas causing minimum flow disturbance. Also, for ease of measurements, the custom probe has been designed to exhibit a linear voltage response to the variation of the tracer concentration such as coloured dye when immersed in a fluid. Useful results were obtained and reported [12]. Herein, the custom built concentration probe is denoted as the Komori probe because of its initial use in the laboratory by Professor Satoru Komori at Kyoto University, Japan.

At QUT, the Komori probes have been used in the laboratory to study the effect of dye mixing and dispersion in a jet stream generated by a propeller [15, 16], to measure the dispersion of exhaust emissions from an outboard motor in a small subtropical creek, and to measure the RTD of a blocked gross pollutant trap. The last two experiments are presented as case studies in this paper, to demonstrate the usage of the Komori probe measuring system, see Section 5.

From the experiments conducted at QUT, it was found that apart from the relatively low manufacturing costs [AUD$ 10-15k for five probes in 2005] the Komori probes are easily deployable in laboratory and field studies and the tracer dye is an organic substance (methylene blue). However, issues in its usage have been reported [15, 16]. The probes are subject to drift and noise particularly when sampling in unclean water. Furthermore, little is documented in relation to the Komori probe's frequency response characteristics, the effect of flow velocity on the frequency response and the quality of data sampled. It is unknown to what extent these factors will consequentially influence the data measured by the probe.

The purpose of this paper is to investigate the frequency response characteristics of the Komori probe. To this end, the time series data is collected from the probe by injecting dye over a range of typical flow velocities and analysed. Noise and frequency response are then determined. Despite noise and drift, the data collected from the probe is useful because of its high frequency response in comparison to other types of tracer measurements. The rise and fall times are reported and compared with the theoretical response time. It was found that the frequency response is a strong function of the fluid flow velocity and frequency response for rise is higher (100 Hz) than that for the fall period (60Hz) under typical operating conditions.

2 Experimental Method

The Komori probe frequency response experiments were performed in the 19m tilting flume at the QUT hydraulic laboratory. Water was supplied to the flume by the choice of three variable speed pumps at the set flow rate. The downstream weir arrangement (not illustrated) was used to regulate the water depth in the flume.

The experimental setup is shown in Fig. 1. A Sontek 16 MHz Micro Acoustic Doppler Velocimeter (ADV) was used to measure the mean fluid velocities (Fig. 1). The dye measuring system comprises: a voltage supply with zero adjustment (Fig. 2 (a), a Komori probe [Fig. 2 (b)], an injection unit and a data acquisition system (Data Translation - DT9802, not illustrated). The injection unit consists of a

Fig. 1: The Komori probe frequency response experimental setup in the flume.

volumetric infusion pump (Alaris Medical Systems - formerly IVAC Corp. Model 597), a dye outlet probe/ injector tube and an intravenous (IV)/ infusion bag filled with blue dye. The Komori probe is fabricated from a hollow stainless rod of 500 mm in length. The external diameter of the rod casing is 6 mm and attached to the probe end is a sampling volume of 75 mm^3, coupled with a polarising lens (mirror), a light emitting diode and photodiode [Fig. 2 (c)]. The end features of the Komori probe measure the opacity of the fluid in which dye is dissolved through the attenuation and reflection of light. The opacity of the fluid is a measure of dye concentration. The organic methylene blue dye is considered to be the most effective tracer substance when used with the Komori measuring system due to a linear voltage response feature. For the purpose of conducting experiments, the concentration of methylene blue dye was diluted to 25,000 parts-per-million (ppm) which is sufficient to allow a maximum detection of 8 ppm when injected and mixed into a volume of water inside the flume. The 8 ppm is the maximum
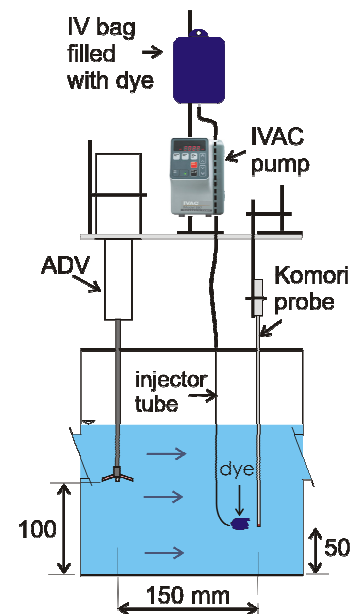
detection range of the Komori probe. Prior to taking measurements, the Komori probe is calibrated by measuring the output sensing voltage in clean water (0 ppm) and in a solution of known concentration i.e. 8 ppm. The corrections for both the solutions (clean water and known concentration) are performed using meters and zero adjustments [labelled as "c.min" and "c.max" as shown in Fig. 2 (a)] on the controller (voltage supply unit). The calibration process is repeated several times.

Two sets of experiments were performed herein, denoted Expt-A (higher flow rates with the infusion pump output set to 20 mL/ h) and Expt-B (lower flow rates with the infusion pump output set to 10 mL/ h). Data was sampled at 20 kHz with the data acquisition system as previously described. The injection probe (Fig. 1) was placed upstream of the Komori concentration probe, at a distance of 50 mm for Expt-A (high flow rates) and 100 mm for Expt-B (low flow rates).

(a)
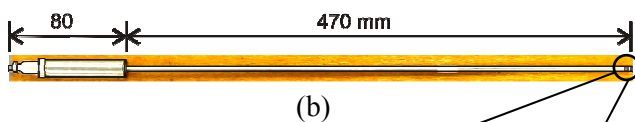
(b)
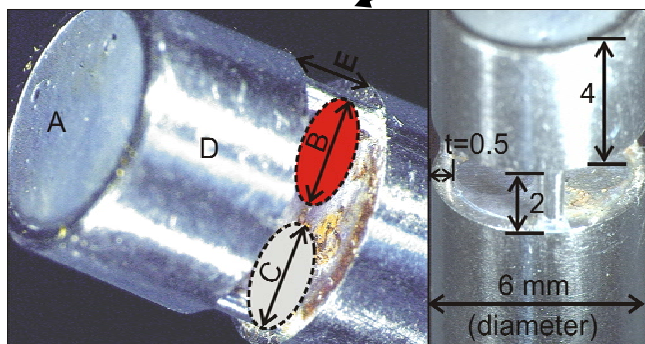
(c)

Key features: **A**-Polarising lens/ internal mirror, **B**-Light emitting diode (2 mm diameter), **C**-Light sensor (photodiode), (2 mm diameter), **D**-Sampling volume enclosure (height = 4 mm) and **E**-aperture opening (2 mm). The thickness t is the distance

between the outer casing to the inner edge of the diode/ sensor (0.5 mm).

Fig. 2: The Komori (scalar dye concentration) controller (voltage supply unit) (a), the dye probe (b), the essential measurement features and the dimensions (c).

3 Frequency Response Method and Analysis

Studies relating to the frequency response characteristics of devices are well documented. For example, a simple response time test on chemiluminescents (CLAs) revealed a typical frequency response of 1 Hz [17]. For the measurement of frequency response of CLA, originally developed by [19], both time and frequency domain methods were applied [6]. In the frequency domain analysis, the CLA is assumed to be a constant parameter linear system ([3], [23]) where a linear relationship between concentration and voltage in steady state response exists. The signals from CLA and a reference cold wire (CW) were processed using a FFT algorithm and the corresponding energy spectra obtained. While in time domain analysis, experiments were performed by specifying a step input to the CLA and finding the time constant for the response of the CLA to rise to 63.1% (= $(1-e^{-1})$x100%) of its final value. Such methods require a known input signal which is not possible in this case. A list showing the various attributes of outputs curves are documented [20] and convenient definitions are provided for these attributes to be measured with unusual shaped output curves.

The frequency response measurement of a photodiode using an optical and mechanical frequency response calibrator (1 KHz to 25 Mhz) was described [24], and [8] applies laser optics for high speed photo-detectors. A similar approach on the Komori probe cannot be used as the effects of fluid interaction and dynamics with the probe are not taken into account. Furthermore, the frequencies for the given range of fluid velocities are much lower than those studied earlier [8, 24]. It is considered appropriate to analyse the measurement response of the Komori probe as a function of fluid velocity and to simultaneously test the reliability of the real time data series sampled. With regard to the input signal, it is assumed that the injection of dye at any instant approximates a square wave. The measuring attributes (the peak detection of dye concentration) of the Komori probe is the outcome in response (rise and fall

curves) to the square wave input. For example a well defined rise and fall curve (Fig. 5) has a sharp peak. However, if the detection of dye is partial (Fig. 6) and the true measured peak is not captured, the experimental data is rejected. The turbulent nature of the surrounding fluid interaction with the intrusive nature of the probe causes the dye to be only partially detected as shown in Fig. 6. The orientation of the probe's measuring system [light emitter diode and photodiode, see B & C in Fig. 2(c)] and its alignment with the direction of flow can also contribute to the partial detection of dye and in this case a distinct plateau in the rise portion of the curve is noted during experiments.

The rise and fall response times are extrapolated from the experimental data using five different methods (Fig. 3). The methods, described in terms of the percentage of the measured peak height (ppm), are classified as: (0 ~ 95%), (0 ~ 1-1/e), (0 ~ 50%), (10 ~ 95%) and (5 ~ 95%), denoted herein as FrmA, FrmB, FrmC, FrmD and FrmE respectively (Fig. 3). Methods FrmB and FrmC are conservative in their approach but useful if there are measurement uncertainties in detecting peak values.
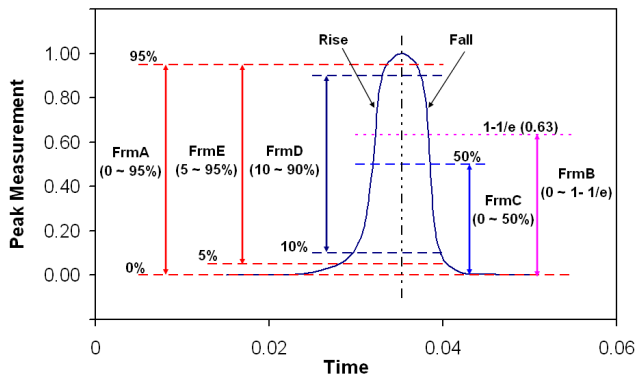

Fig. 3: The frequency response methods shown in graphical form, used on data sampled by the Komori probe.
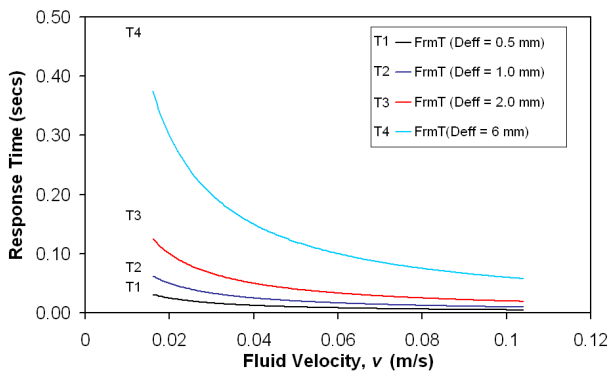

Fig. 4. Theoretical frequency response curves for effective measurement width D_{eff} = 0.5, 1, 2 & 6 mm.

For a given flow rate, the theoretical frequency response is the effective time it takes the dye to travel across the light sensor [photodiode, see C in Fig. 2(c)] in the sampling volume [the aperture and the sampling volume enclosure, see D & E in Fig. 2(c)], ignoring the interaction between the probe and the fluid. The cross sectional width of the photodiode is 2 mm and the height of the sampling volume (SV) is 6 mm. The effective time i.e. the theoretical frequency response time [FrmT (secs)] is expressed as follows:

$$FrmT = \frac{D_{eff}}{v} \qquad (1)$$

Where v is the fluid velocity m/s and D_{eff} (m) is the effective distance.
The experimental results suggest that under varying flow rates, D_{eff} is a function of fluid velocity. To this extent four distinct values for D_{eff} (0.5, 1.0, 2.0 and 6.0 mm) are used in (1) to calculate FrmTs and are plotted in Fig. 4.
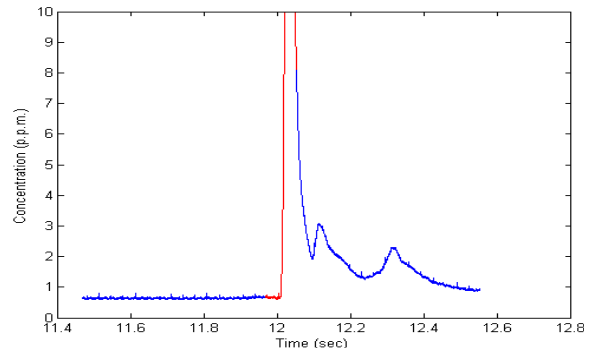

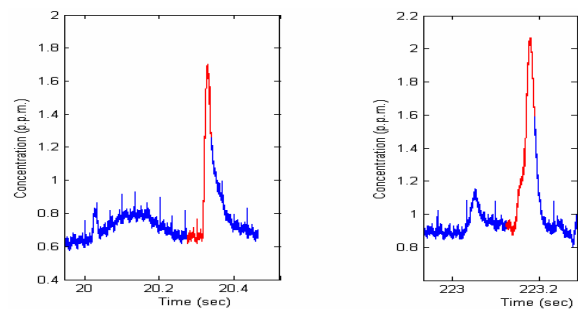Fig. 5: A typical data plot showing a sharply defined rise peak.

Fig. 6: Typical experimental data plots showing false peaks caused by the partial detection of dye.

4 Results and Discussions

Table 1 contains a summary of the number of rise and fall curves detected and the experimental setup conditions (water depth, fluid flow velocities and the flow rate of the dye pump).

The statistical mean response times for each batch of rise and fall curves are plotted in Figs 7 and 8 with the theoretical response times for D_{eff}

(0.5, 1, 2 and 6 mm). For the purpose of graphical clarity, the rise and fall plots do not have the same frequency response axes scale.

Table 1: Summary of frequency response tests performed, Expt-A (tests 1-5) and Expt-B (tests 6-9).

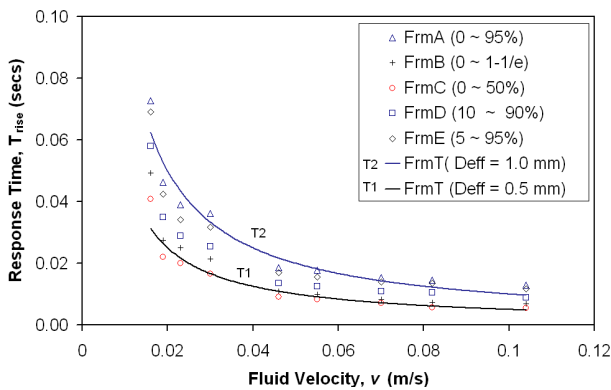| Test	Water Depth (mm)	Water Velocity (m/s)	Dye pump flow rate (mL/h)	Rise curves (No.)	Fall curves (No.)
1	221	0.046	20	118	70
2	191	0.055	20	143	86
3	161	0.070	20	134	69
4	131	0.082	20	184	109
5	112	0.104	20	237	139
6	190	0.016	10	46	33
7	223	0.019	10	73	56
8	160	0.023	10	127	70
9	130	0.030	10	176	111

Fig. 7: Comparison of experimental rise data (FrmA, FrmB, Frmc, FrmD, FrmE) with theoretical frequency response (FrmTs, D_{eff} = 0.5 & 1.0 mm).
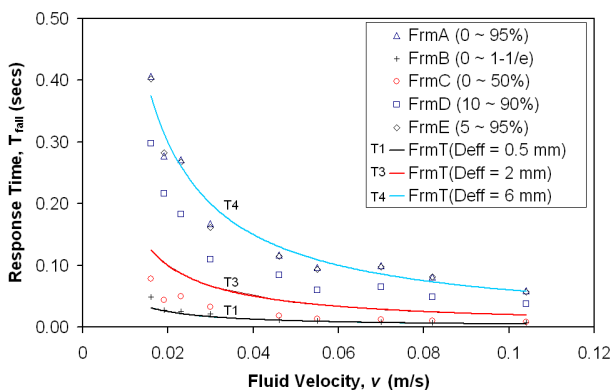

Fig 8: Comparison of the experimental fall data (FrmA, FrmB, Frmc, FrmD, FrmE) with theoretical frequency response (FrmTs, D_{eff} = 0.5, 2 & 6 mm).

Figs 7 and 8 show that the frequency response of Komori probe characteristic is a function of the fluid velocity. In regions where the flow velocities

are greater than 0.04 m/s the data appears to be almost linear and measurement is more suitable within this range. In Fig. 7, the mean rise response curves for the methods (FrmB-C) show a maximum frequency response of 100 Hz, the lowest is 60 Hz (FrmA). Similarly for the fall curves (FrmB-C) the maximum frequency response is 60 Hz and the lowest is 10 Hz (FrmA) as indicated in Fig. 8. It is noted from Fig. 7 the experimental rise data falls between D_{eff} = 0.5 and 1 mm. The D_{eff} for the fall curves lies between 0.5 and 6 mm (Fig. 8). It is unclear whether the slower response time is attributed to the retarded behaviour of the dye injected fluid dissipating from the sampling volume enclosure [see D in Fig. 2 (c)].

Measurement uncertainties are also noted in areas relating to the probe's orientation with respect to the direction of fluid flow and the surrounding flow disturbance effects. Signal noise levels in the sampling data needed to be addressed. Remedial measures were taken by using differential input connections, grounding the probe casing and using a filtering system to remove unwanted fine particles in the flume. It is unknown to what extent the residual coating of the dye on the surface of the probe casing and sensors' mounts will influence the readings. No cleaning specifications have been supplied by the manufacture to suggest otherwise.

Table 2. Rise and fall time constants using the five methods (see equation 2), and E is the measurement uncertainty (equation 3).

FrmX	Rise		Fall	
	A_c (mm)	E (%)	A_c (mm)	E (%)
FrmA (0 ~ 95%)	1.05	13.0	5.94	11.0
FrmB (0 ~ 1- 1/e)	0.61	11.0	1.33	13.0
FrmC (0 ~ 50%)	0.49	11.0	0.92	14.0
FrmD (10 ~ 90%)	0.76	12.0	4.00	9.0
FrmE (5 ~ 95%)	0.95	14.0	5.85	11.0

A power law relationship expresses the relationship between velocity and frequency response as follows:

$$FrmX(v) = A_c / v, \qquad (2)$$

where X = A, B, C, D or E, A_c is a constant. The measurement uncertainty (error) is expressed as:

$$E = \frac{FrmX_{predicted} - FrmX_{measured}}{FrmX_{measured}} \times 100\% \qquad (3)$$

In table 2, the constant A_c and the error (%) are within 95% confidence limits. The maximum and minimum rise and fall trend curves (FrmA-B) are plotted with the theoretical values (FrmT D_{eff} = 0.5,

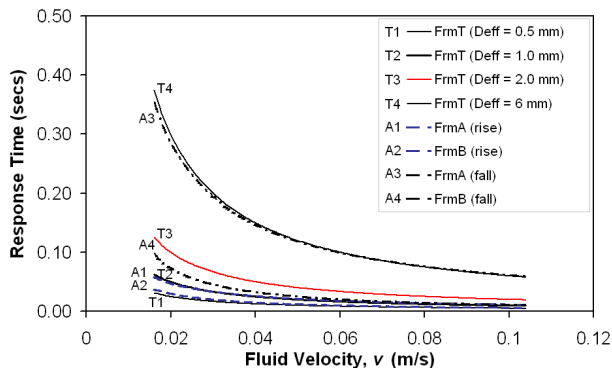1, 2 and 6 mm) in Fig. 9 and shows good correlation.

Fig.9: Experimental and theoretical frequency response curves (FrmA-B & FrmT D_{eff} = 0.5, 1, 2 & 6 mm) with 95% confidence prediction limits.
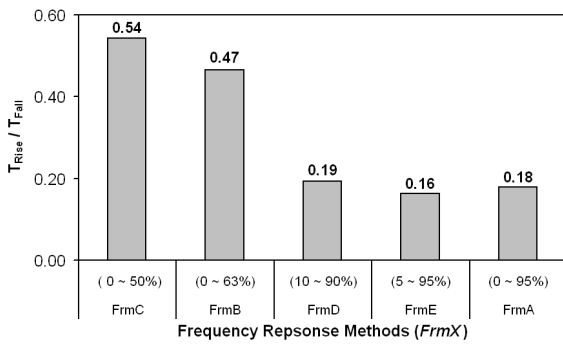

Fig. 10: A histogram of the rise and fall response time ratio and the corresponding frequency response methods.
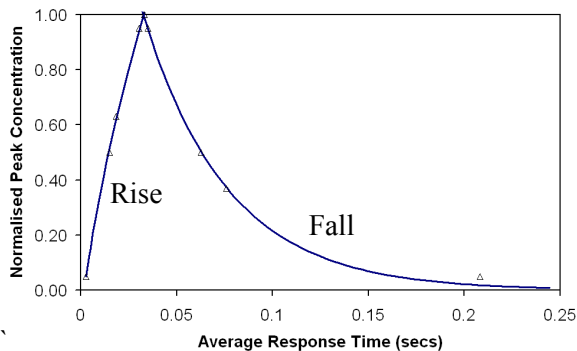

Fig. 11: Average experimental rise and fall response times.

The ratio between the rise and fall data and the FrmXs are plotted in Fig. 10. Fig. 10 initially indicates that for FrmC, the rise time is 54% of the fall time. As the response criteria changes to FrmB, there is a 7% decrease in the ratio between rise and fall data response times. When the bandwidth of response time method increases towards 90% of the measured peak value, there is a rapid increase in the fall data response time. Consequently a stable plateau is reached where the rise time becomes less than 20% of the fall time for the remaining FrmXs

i.e. FrmA, FrmD and FrmE. The fall curve has an exponential decaying behaviour towards the tail end. This is also shown in Fig. 11, where the nominalised peak concentration is plotted against average response time. The rise time increases rapidly unlike the fall time which decreases more slowly. Fig. 11 also compares favourably with the typical signal curve as shown in Fig. 5.

5 Case Studies

As previously mentioned, the Komori probes have been deployed by QUT, to study the effects of mixing and dispersion of pollutants in water, due to outboard motor exhaust emissions, and also to measure the RTD in a blocked gross pollutant trap (GPT). These case studies are respectively described below in Sections 5.1 and 5.2.

5.1 Dispersion of exhaust emissions from an outboard motor

(a)
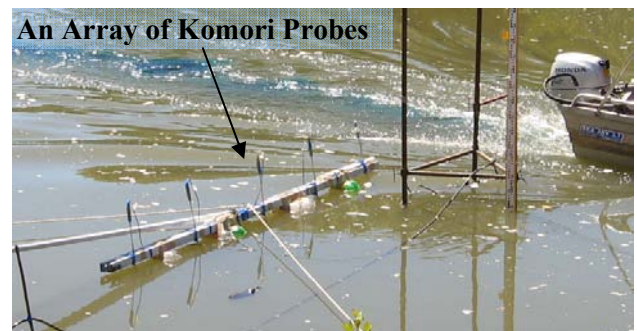
(b)

Fig. 12: (a) Measuring the dispersion of blue dye from an outboard motor (b) A closer view of the Komori probes and the boat stern with the outboard motor (Honda).

Exhaust emissions from outboard motors are known to have a detrimental effect on polluting the

waterways [11]. Field experiments were carried out in a small subtropical creek (Eprapah Creek) located at Victoria Point in Queensland. These measurements are part of an extensive series of measurements by [7, 25]. The dispersion rate of exhaust emissions from outboard motors is measured by injecting the tracer (methylene blue dye) into the region of propeller wake from the boat (Fig. 12). The wake generated by the propeller and boat transports the dye laterally past an array of Komori probes. Here the dye peak concentration is detected in a time series plot as shown in Fig. 13. The time scale on the horizontal axis relates to point at which the boat passes the probes. Data is recorded on a computer via an A/D converter and the sampling rate is 10 kHz.

A critical aspect of this experiment is to use a probe with an adequate frequency response to detect the peak concentrations that occur in the highly fluctuating flow behind an outboard motor. Results from Section 4 (Fig. 4) show that the probe is capable of measuring frequency response of up to 100 Hz at velocities of 0.1 m/s. Beyond 0.1 m/s the frequency response of the probe appears to be unaffected by the water velocity. For the outboard field experiments, velocities in excess of this level were noted in certain regions. We need to determine if the frequency response of the probe is sufficient for outboard motor experiments.
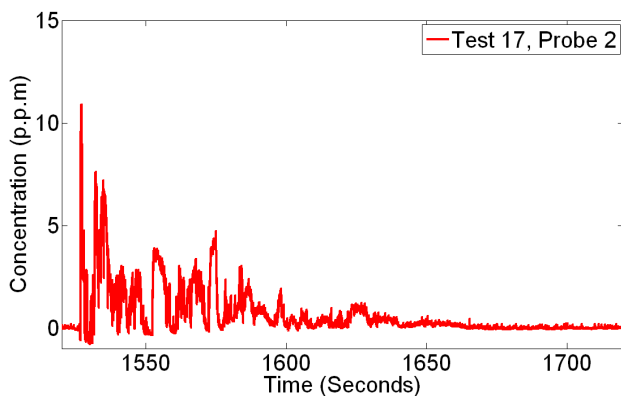

Fig. 13: An example of a time series graph with peak concentration dye measurement from one of probes shown in Fig 12 (b).

In an attempt to assess the quality of data sampled at the higher frequency, the raw data plotted in Fig. 13 is re-plotted in Fig. 14 by finding the maximum (peak) concentration in each successive 10 second window period. In Fig. 14 consistent peak concentration decay is shown with time. If a number of frequency response points was insufficient close to time = 0 (seconds), the measured peak would be truncated, i.e. the graph

would show a plateaux and not a sharp peak at time = 0 (seconds). It can be observed that this is not the case indicating that frequency response is adequate for this experiment.
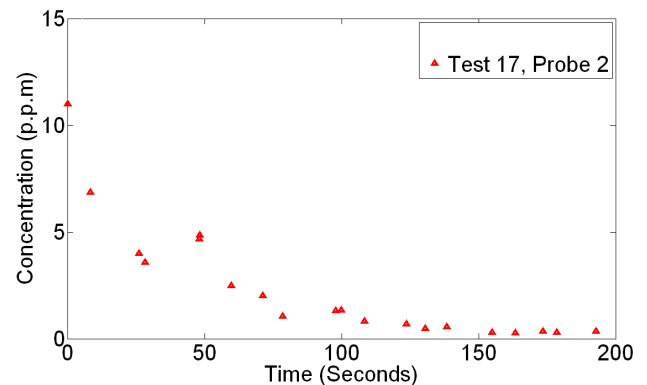

Fig. 14: Maximum concentration in each successive 10 second window corresponding to the data in Fig.13.

5.2 Investigating dye mixing and dispersion in a blocked gross pollutant trap (GPT).
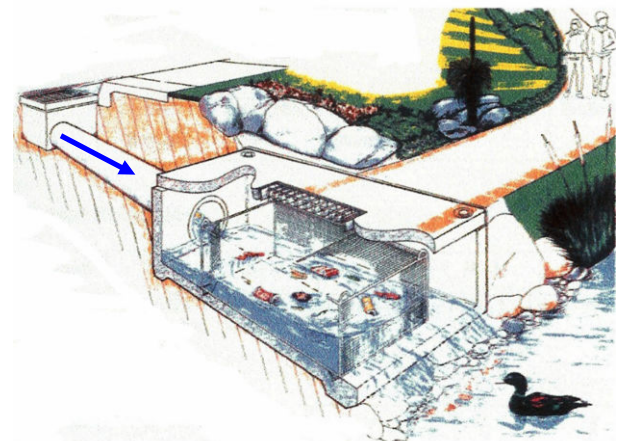

Fig. 15: SQID (GPT) – LitterBank insitu.

Gross pollutant traps (GPTs) are widely used to remove litter from storm water. A GPT *LitterBank* shown in Fig. 15 was recently developed by C-M Concrete Pty. Ltd in 2004. The LitterBank design uses retaining screens to collect gross pollutants from the incoming storm water (Fig 16).

Field studies show that retaining screens in GPTs are commonly blocked with organic matter due to infrequent cleaning, and can radically change the litter retention characteristics and flow structure within the GPT, leading to large recirculating flow patterns within the trap area, accompanied by hydraulic short circuiting where the outflow path is via the by-pass channel (Fig. 16). Dye mixing and dispersion experiments in a GPT with fully blocked screens were carried out to

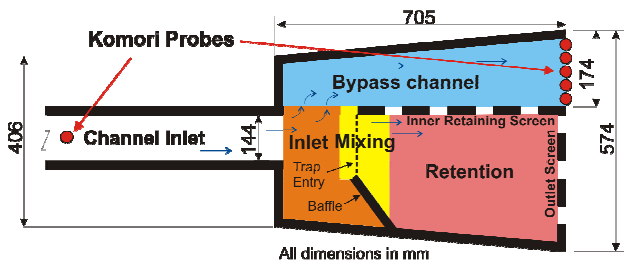understand the litter retention characteristics in this mode of operation.

Fig 16. Plan view of LitterBank Scale Model with the Komori probes at inlet and outlet.

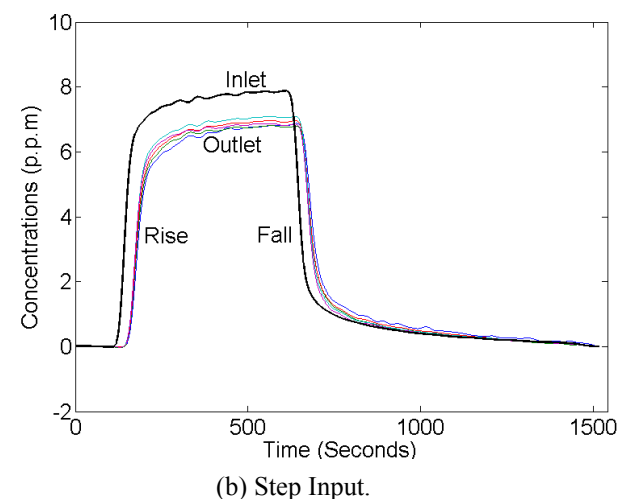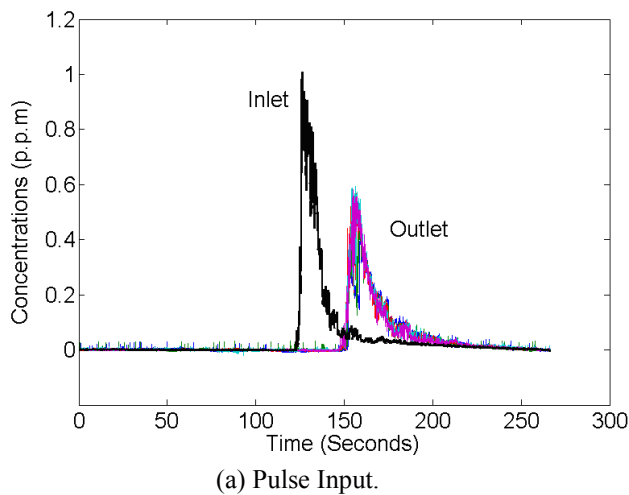(a) Pulse Input.

(b) Step Input.

Fig. 17: Time series of peak concentration measurements obtained by introducing dye (a) instantaneously (pulse input) and (b) continuously (step input).

The experiments were conducted in a 50% scale model placed in a 19m tilting hydraulic flume at QUT. To measure the peak concentrations of dye entering into the scale model, a single Komori probe was placed in the channel inlet whilst an array was positioned at the outlet in by pass

channel as shown in Fig 16. The blue dye was introduced upstream of the channel inlet in separate experiments using two methods: (a) instantaneously (pulse) and (b) continuously (step). At the inlet, the flow rate was maintained at 1 L/s (i.e. the inlet velocity is 0.07 m/s). The measured peak dye concentration is shown in a time series plots (Fig. 17) for the two methods of inputs, i.e. pulse and step with a sampling frequency of 200 Hz. There are two parts to the output curve shown in Fig. 17 (b) i.e. when the dye pump is on (rise) and off (fall). Data plots in 17 (b) have been filtered for noise and drift.

The dominant frequency of the inlet and outlet concentration time series in Fig. 17 (a) and (b) are respectively around 0.03 and 0.02 Hz. Unfiltered data in Fig. 17 (a) shows additional high frequency fluctuations. It is shown that the probe is well within its frequency response capability to measure the dominant frequencies in this case study. Overall the study shows that the Komori probe is versatile in measuring in range of frequencies and flow velocities.

6 Conclusion

In this work, the frequency response characteristic of the scalar (dye) concentration probe of Komori is evaluated by injecting methylene blue dye into the flume over a range of typical flow velocities. The data sampled by the Komori probe is subjected to time series analysis and the statistical mean response times for the rise and fall curves are determined. It was found that the frequency response is a strong function of the fluid flow velocity and the maximum frequency response for the rise is higher (100 Hz) than for the fall period (60Hz) for the measured flow velocities (Figs 7-8). The corresponding minimum values are 60 Hz (rise) and 10 Hz (fall). The theoretical frequency response FrmT is based on the characteristic probe dimension, defined as the effective dimension D_{eff}. It is found that the experimental data fits within an effective dimension of $D_{eff} = 0.5$ to 6 mm. The slower fall response time may be attributed to the tendency of the injected dye to remain in the sampling volume enclosure after the peak has passed. The injected dye may also be caught in the boundary layer that forms around the probe mirror and associated surfaces. Further investigation is required to determine the influence of the sampling volume.

Two case studies are presented as examples in the usage of the probes to determine the concentration fluctuations: concentration decay in

the wake of an outboard motor and in a blocked GPT. It is concluded that the Komori probe's frequency response characteristic is sufficient to measure the relevant concentration fluctuations. Further work is planned to continue measurements in evaluating the data obtained from the Komori probes and compare with other tracer methods.

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