13th Australasian Fluid Mechanics Conference
Monash University, Melbourne, Australia
13-18 December 1998

LARGE SCALE TURBULENCE IN SEAGRASS CANOPIES

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ABSTRACT

Single point velocity measurements within and above an artificial seagrass canopy were conducted in a flume under a unidirectional flow of 0.2 m/s. Averaged profiles of the statistical moments, spectra and Eulerian length scales are presented and discussed. These results support the existence of large-scale turbulent coherent structures above the seagrass meadow, with length scales in the order of the height of the canopy h.

INTRODUCTION

Much progress has been made in understanding the nature of turbulence around plant canopies in the medium of air (eg. Raupach and Thom, 1981; Brunet, Finnigan and Raupach, 1994), yet the interaction of water and vegetation is an area of little research. Coastal vegetation such as seagrasses are bent by the dominant fluid motion into a more streamlined shape, resulting in the formation of a dense canopy that re-directs the flow (Fonseca et al., 1982). The resulting flow regime subsequently consists of two distinct layers with varying velocity profiles above and below the canopy, together with the canopy-water interface being a region identified with increased turbulence under current flow (Gambi et al., 1990). Ackerman and Okubo (1993) examined the turbulence intensity of in situ *Zostera marina* seagrass meadows and concluded that mechanical turbulence can be generated at frequencies related to blade movement, found to range between 0.125-0.156 Hz in this situation.

Despite the measurement of velocity and turbulence profiles, there has been little attempt to apply flow theory and to characterise the turbulent behaviour within seagrass meadows. The apparent travelling wave-type motion in flexible vegetation was first identified in crops and entitled a 'honami' phenomena (Inoue, 1955). This periodic waving motion is existent in seagrass meadows. Ikeda and Kanazawa (1996) studied flow structure under unidirectional flow on flexible vegetation and found that a three-dimensional vortex developed immediately above the plant canopy-water interface. The authors suggest that the wavy motion of the vegetation is a product of the movement of organised vortices, also known as coherent turbulent structures. Ikeda and Kanazawa (1996) surmise that periodic organised vortices are generated under an unstable shear flow if the vertical velocity profile has an inflection point; this type of velocity profile is seen to result at the interface of seagrass meadows under unidirectional conditions (Gambi et al., 1990; Wallace and Cox, 1997). The existence of intermittent organised coherent structures above crop canopies is well established (Brunet, Finnigan and Raupach, 1994), and it is this mechanism that largely dominates turbulence within and immediately above the canopy.

This paper presents results of the velocity field, together with energy spectra and Eulerian length scales, confirming the visual assessment of large-scale turbulent coherent structures above seagrass canopies under unidirectional flow. The identification of turbulence processes and momentum transfer at the seagrass canopy-water interface has tremendous physical implications as these processes are largely responsible for oxygen exchange, pollen dispersal and sedimentation within seagrass beds.

THEORY

The Navier Stokes equations govern fluid motion, and for an incompressible flow, they consist of the continuity and momentum equations. Turbulent velocities are typically introduced via a Reynolds decomposition. This decomposition usually consists of the instantaneous velocity (u) being composed of a mean ($\bar{u}$) and fluctuating component (u') based on time averaging, ie.

$$u = \bar{u} + u' \qquad (1)$$

Turbulence intensity is the term given to the root-mean-square (rms) of the fluctuating velocity components, identified as

$$u_{rms} = \sqrt{\overline{u_i' u_i'}} \qquad (2)$$

where the i and j subscripts take values from 1 to 3, representing direction.

The dominant velocity and length scales for mean motion are typically $\bar{u}$ and H, where H is the total water depth. However for turbulence parameters, the shear velocity u_* and bent canopy height h are more appropriate (Raupach and Thom, 1981), where u_* is given by,

$$u_* = \sqrt{\overline{u_i' u_j'}} \qquad (3)$$

The term $\overline{u_i' u_j'}$ represents the turbulent or Reynolds stress normalised by the fluid density. Through applying Taylor's frozen-turbulence hypothesis, important characteristics of the structure of turbulence can be identified using the Eulerian length scales L_u and L_w. These parameters are estimated from the single-point integral time scales T_u and T_w, given below.

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$$L_u = 2\pi \bar{u} T_u = 2\pi \frac{\bar{u}}{u_{rms}^2} \int_o^\infty \overline{u'(r)u'(t+\tau)} d\tau$$

$$L_w = 2\pi \bar{u} T_w = 2\pi \frac{\bar{u}}{w_{rms}^2} \int_o^\infty \overline{w'(r)w'(t+\tau)} d\tau \qquad (4)$$

where τ refers to the time delay or lag, and u and w denote the horizontal and vertical velocities respectively. Note that a factor of 2π has been included in equations (4), as the resultant integral length scale is more representative of the actual eddy size. The above equations are normally integrated to the time of the first zero crossing of the autocovariance function. According to Hinze (1959), the Eulerian length scale is a measure of the most rapid changes that occur in the fluctuations of a velocity component. "The physical interpretation is that if $\bar{u} >> u'$, the fluctuations at a fixed point of the field may be imagined to be caused by the whole turbulent flow passing that point as a 'frozen' field." With the existence of large scale turbulent structures, equation (1) can be further decomposed and expressed as

$$u = \bar{u} + u_c' + u_r' \qquad (5)$$

where u'_c is the component representing large scale turbulence, considered to be periodic with a fixed phase, and u'_r is indicative of smaller-scale random turbulence. It is the large turbulent structure represented by u'_c that is of particular interest in this study.

LABORATORY EXPERIMENTS

A range of experiments at prototype scale under unidirectional flow were conducted in a 30 m long x 0.6 m wide flume. Artificial seagrass based on the species *Posidonia australis* was used to simulate seagrass behaviour, with a stillwater height of 30 cm within a 4m long meadow. Shoot density corresponded to 400 shoots/m^2. A three-dimensional Acoustic Doppler Velocimeter (ADV1) recorded single-point high resolution velocity measurements sampled at 25 Hz, for a duration of 5 minutes. The ADV1 was positioned at varying locations outside and within the meadow, as demonstrated in Figure 1. Velocities were recorded throughout the water column, commencing 5 cm off the bed with sampling intervals every 1 cm below the canopy, then profiles every 2-3 cm until the water surface. This range of experiments were conducted under a mean flow of 0.2 m/s. The theoretical accuracy of the ADV1 is specified to ±1% of the measured velocity.

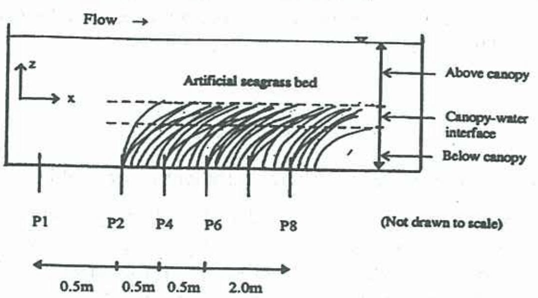

Figure 1: Schematic diagram of laboratory flume and experimental layout.

The orientation of the experiment is such that x is the streamwise direction, y the cross-stream coordinate, and z in the vertical plane (z=0 at the bed). The commencement of the canopy is identified at P2 as x=0, with the three recording locations at the following distances into the meadow: P4 (+0.5m), P6 (+1.0m), and P8 (+3.0m).

RESULTS

Velocity Field

An example of the time-averaged mean longitudinal velocity (u) profile is shown in Figure 2, along with the

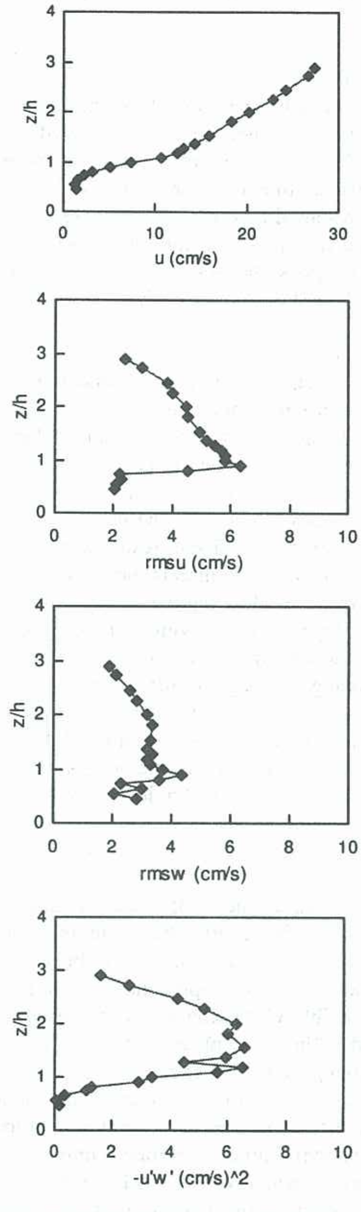

Figure 2: An example of mean longitudinal velocity $\bar{u}$, u_{rms} and w_{rms}, and turbulent stress profiles at P8, where z/h is non-dimensionalised height above the bed.

corresponding turbulence intensities u_{rms} and w_{rms}, and the turbulent stress. The bent canopy height was h=11 cm, and the total water depth was 40 cm. The shear velocity u_*, was determined from equation (3) at the control position (ie. without the influence of the canopy at P1), and was found to be 1.5 cm/s. Mean longitudinal velocities were seen to decrease to nearly zero under the canopy, with the flow redirected over the canopy, producing an increase in velocity. An inflection point in the mean velocity $\bar{u}$ profile is evident at the plant canopy interface. Maximum turbulence intensities typically occur near the plant-water interface, and maximum turbulent stress was relatively constant in a layer ranging between h<z<2h. There is strong inhomogeneity in u'w', and u_{rms} and w_{rms}. These findings were consistent throughout the recording locations within the meadow. In regard to the reliability of the experimental data, Voulgaris and Trowbridge (1998) evaluated the accuracy of the ADV for turbulence measurements and stated that the instrument can measure mean velocity and Reynolds stress within 1% of the estimated true value.

Length Scales and Spectra

In order to focus primarily on the large scale turbulence, the mean velocity was removed from the velocity signal, and the subsequent velocity time series was both lowpass (5Hz cutoff) and highpass filtered (0.15Hz cutoff) using a seventh-order Chebyshev type 1 filter, and then corrected to ensure a zero-phase shift. This procedure ensured that only the large scale turbulent component (u'_c) remained.

The single-point Eulerian length scales L_u and L_w were determined from the filtered data using equations (4), where the autocorrelation functions were computed for the u and w components at each depth throughout the water column. A comparison of the calculated autocorrelation functions with those described in Townsend (1976), identifies the turbulence as predominantly being either two-dimensional or consisting of two distinct ranges of eddy sizes, which is later further substantiated by the power spectra. Figure 3 displays profiles of the two turbulent length scales throughout the water column at three distances into the meadow.

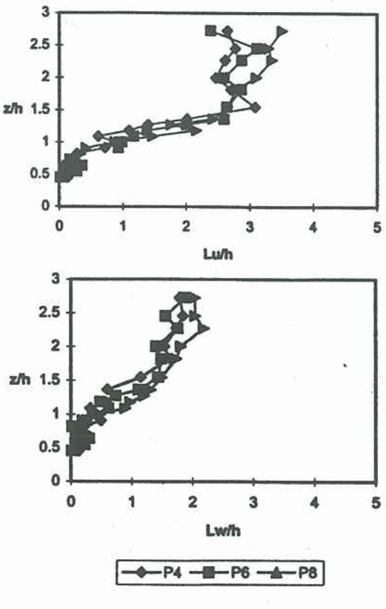

Figure 3: Eulerian horizontal and vertical integral length scale profiles.

These figures demonstrate that L_u and L_w increase with height until approximately z/h≥1.5. At the top of the canopy (z/h=1), the length scales are of the order L_u=h, and L_w≈h/2. Future work using additional velocity sensors will focus on how long (or over what distances) these large eddies retain their structure by examining space-time correlations.

Power spectra were examined to further assess the large-scale eddy motion above the canopy, and to indicate dominant frequencies of vortex motion. The spectra plots shown here were averaged from seven spectra, composed of contiguous time series of 1024 points from the original filtered record. Figure 4 displays filtered power spectra resulting from the longitudinal velocity measurements from heights beneath, at the interface and above the canopy, at position P8 (+3.0 m).

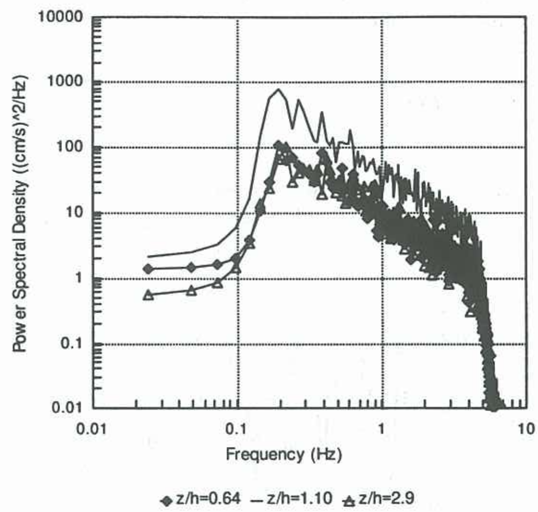

Figure 4: Power spectral density for longitudinal flow velocity at various non-dimensionalised heights above the bed at P8. (z/h=1 is the canopy interface).

The above figure demonstrates the increased energy at the height immediately above the canopy, supporting the presence of energetic turbulent structures within this region as indicated by the turbulent stress profile in Figure 2.

Summarising the streamwise component power spectra for all three sampling positions, it was evident that the peak frequencies (f) occur between the range of approximately 0.2-0.6 Hz. The corresponding period range T is 5.0-1.7 secs, where T=1/f. However, multiple peaks frequently occurred within this frequency band at sampling depths nearing the top of the canopy and above, corresponding to the average depth range of 0.82<z/h<2.0. An example can be seen in Figure 5 for the profile at z/h=1.10 at P8 (+3.0 m).

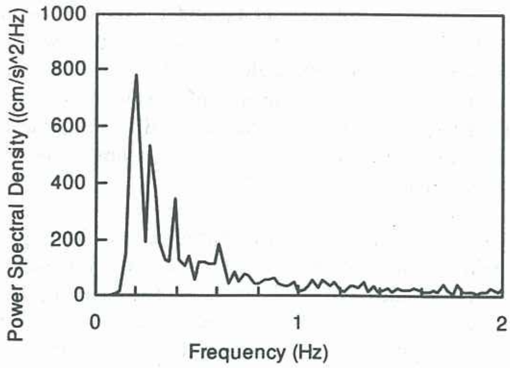

Figure 5: Linear streamwise velocity power spectral density plot of z/h=1.10 at P8.

A possible analogy for the consistent multiple peak pattern can be demonstrated by representing a series of consecutive eddies with a function F(t) consisting of a sine wave of the following form:

$$F(t) = \sin\frac{2\pi t}{T}\left|\sin\frac{2\pi t}{2T}\right|^{\alpha} \qquad (6)$$

where α is a positive constant and t is time. Figure 6 demonstrates a time plot and the associated power spectra for a function of the above form when T=5 secs and α=6.

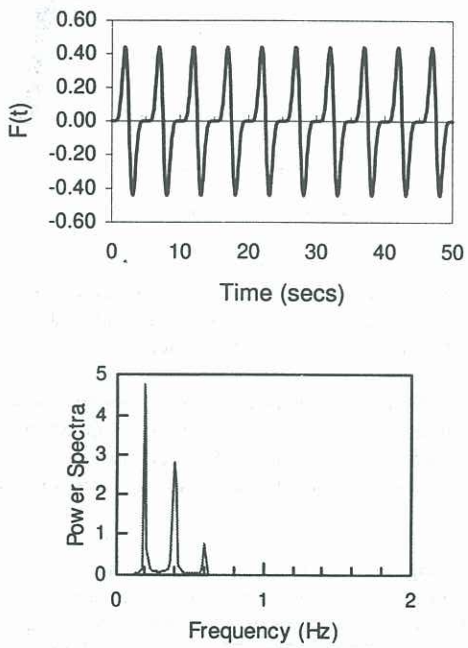

Figure 6: Time series and Power Spectra of wave of the form of equation (6), with T=5 secs and α=6.

The time series profile in Figure 6 represents the existence of not only the spacing of the eddies (L_s), but also periodic behaviour within each eddy (ie. eddy period). A series of multiple peaks were found to occur if the power spectra was calculated for the above function in equation (6), with the lowest frequency peak (f_1) in Figure 6 representing the eddy separation or spacing frequency.

Applying this logic to the lowest frequency peak in the measured streamwise velocity spectra (Figure 5) allows the eddy spacing L_s immediately above the canopy-water interface to be determined as ~50 cm or in the order of 5h, where $L_s=u/f_1$, u=10 cm/s (Figure 2) and f_1=0.2 Hz (Figure 5). Hence $L_s \approx 5L_u$, since at the top of the canopy L_u was found to be in the order of h (Figure 3). From f_1, an eddy spacing period T of 5 secs can be estimated.

While application of the analogy shown in Figure 6 is somewhat tenuous, it is supported by visual assessments which showed the honami interval during experiments to vary between 3-5 seconds, coinciding with the spectral peak period range of 2-5 secs.

CONCLUSION

The momentum transfer within seagrass meadows under unidirectional flow is dominated by large coherent eddies at the plant-water interface and extending above the seagrass meadow, with Eulerian length scales of the order of bent canopy height h. Analysis of the streamwise velocity spectra indicated a maximum period of approximately 5 secs could be inferred to govern the spacing of the turbulent structures, which related to a streamwise eddy spacing length scale in the order of 5h in the vicinity of the canopy interface.

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