

Estimating Surf Zone Turbulence 2003 REU Project

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Abstract

A laboratory study of surf zone velocities is used to compare two common methods of estimating turbulence, ensemble averaging and frequency filtering. It was found that ensemble averaging produces inaccurate estimates if wave irregularities are present. Consequently, it is critical to assess wave regularity before applying this method. Frequency filtering proves to be more accurate for slightly irregular waves, but determination of cutoff frequency is important and deserves further research.

1. Introduction

Wave breaking converts ordered wave energy into disordered turbulent energy. Turbulence generated by breaking waves is linked to sediment suspension, a critical factor in beach erosion. Various methods have been employed to understand the nature of surf zone turbulence. Flow visualization techniques have yielded general knowledge regarding the development of turbulence. For example, breaking processes have been dynamically modeled using ultraviolet light to illuminate fluorescent particles (Jansen, 1986). Both the formation and structure of large scale eddies are explored by Nadoaka (1982). However, due to the complex nature of turbulence, it is difficult to quantify. Turbulence occupies a large, undefined range of length and time scales. In addition, wave induced motion obscures attempts to isolate turbulence.

With the advent of better ways to measure water particle velocities, turbulence estimation techniques have improved. Accurate velocity records provide a solid foundation on which to develop methods to isolate turbulence. Methods such as ensemble averaging and frequency filtering are commonly employed and other methods are currently being developed.

At present, these methods of estimating turbulence have not been compared against one another. This paper highlights four of these methods. Also, ensemble averaging and frequency filtering are compared based on results obtained from a laboratory study.

2. Theory

Moving shoreward through the surf zone, organized wave energy degenerates into turbulence as waves break. However, this process is not instantaneous; varying magnitudes of wave motion and turbulent motion are present throughout the surf zone. The crux of estimating turbulence is to isolate turbulent motion from wave-induced motion. However, the two types of motion are not clearly defined. Wave motion and turbulent motion occupy overlapping time scales and length scales. Consequently, there is no single fail-proof way to estimate turbulence in the surf zone.

Here, four methods are summarized. Each method has advantages as well as limitations. The purpose of this study is to determine the extent to which these limitations affect reasonable estimates of turbulence.

2.1 Ensemble Average

Ensemble averaging is commonly used in laboratory experiments. It is a widely accepted method for estimating turbulence created by monochromatic waves. By assessing the repeatability of velocity fluctuations, ensemble averaging separates wave motion (repeated wave to wave) from turbulent motion (not repeated wave to wave).

It is noted that ensemble averaging is able to remove all repeated patterns, no matter how complex they may be (Svendsen, 1987). However, there are drawbacks. Ensemble averaging

relies heavily on highly-uniform monochromatic waves, preventing field application. Any deviation in wave period, size, or breaking location will inflate the estimate of turbulence. As the wave period in the surf zone is not constant (Svendsen, 1987), turbulence is overestimated.

2.2 Frequency Filter

Whereas ensemble averaging is common in laboratory settings, frequency filtering is common in the field. Frequency filtering separates wave motion from turbulent motion based on frequency. Once a reasonable cutoff frequency, f_c , is decided upon, motions at frequencies lower than f_c are considered to be wave-induced. The remaining higher-frequency motions are said to represent turbulence. This is usually accomplished with an ideal high-pass filter.

Frequency filtering has the advantage that it distinctly separates low and high frequency motion. This can also present difficulties, particularly when determining f_c . It is known that large scale eddies account for a significant portion of the turbulent energy under a breaking wave. Often, the time scales of these large eddies are close to f_c . A high f_c has the potential to exclude large eddies from the estimation of turbulence. Conversely, a low f_c may include wave-induced motion in the estimation of turbulence. Thus, the frequency cutoff must be selected judiciously.

For this study, the cutoff frequency is based on the frequency of the wave, f_w . This choice is based on the hypothesis that turbulent time scales are defined by wave period. Further analysis will examine f_c derived from the “local wave height of bore,” based on Nadaoka’s deductions (1982).

2.3 Correlation with the Free Surface

Correlation with the free surface can also be used to estimate turbulence. While it is not as widely used, this method has practical merit. Velocity records are compared with records of the free surface by means of numerical filtering. Motion that is correlated with the free surface is considered wave-induced; uncorrelated motion is considered turbulent.

It is noted that correlation with the free surface is likely to produce “results similar to an ensemble averaging.” (Svendsen, 1982) Similarities exist between the two methods. However, correlation with the free surface examines each individual wave based on its unique characteristics. It does not require monochromatic waves as ensemble averaging does. Correlation with the free surface has estimated turbulence in the surf zone with some success (Rodriguez, 1999).

2.4 Trowbridge’s Method

Of these four methods, Trowbridge’s method is the newest. *On a Technique for Measurement of Turbulent Shear Stress in the Presence of Surface Waves* describes an innovative method of estimating turbulence (Trowbridge, 1998). This technique is based on the covariance between two velocimeters, separated by a critical distance and positioned near bottom. It distinguishes wave-induced motion (detected by both sensors) from turbulence (detected by a single sensor). It also corrects any slight misalignment of the sensors.

Trowbridge’s method appears to have potential, as it can be used in field as well as the laboratory. Since introducing the method in 1998, Trowbridge has continued to use it for other studies (Trowbridge, 2001, 2003). Since this method is relatively new, it has not been explored as thoroughly as other methods.

3. Experiment

A laboratory experiment was conducted at Oregon State University using O.H. Hinsdale Wave Research Laboratory's large wave flume. The 104 m long by 3.7 m wide by 4.6 m deep flume is equipped with a programmable flap-type wavemaker. Wave breaking was induced using a fixed 1:12 slope shown by Figure 1. The flume was filled to a depth of 3.32 m with tap water.

Eight capacitance-type surface-piercing wave gages were used to measure the free surface. Two SonTek MicroADVs, located across the tank from one another, were used to measure instantaneous velocities in each direction. Shoreward velocity was defined as u , upward velocity defined as w , with v defined by a right-handed coordinate system. Sensor locations are defined in Figure 2. The primary sensor area contained identical sensors on each side of the tank. Each side had three wave gages offset by 3 ft, with one ADV mounted directly beneath the center wave gage. A single wave gage was positioned at the toe of the slope to measure incident waves, while another wave gage was placed near breaking.

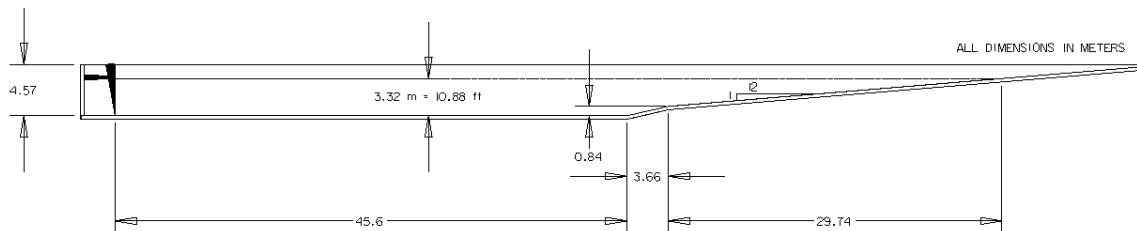


Figure 1: Experimental Tank Configuration. Programmable flap-type wavemaker produces waves which break on fixed 1:12 impermeable slope.

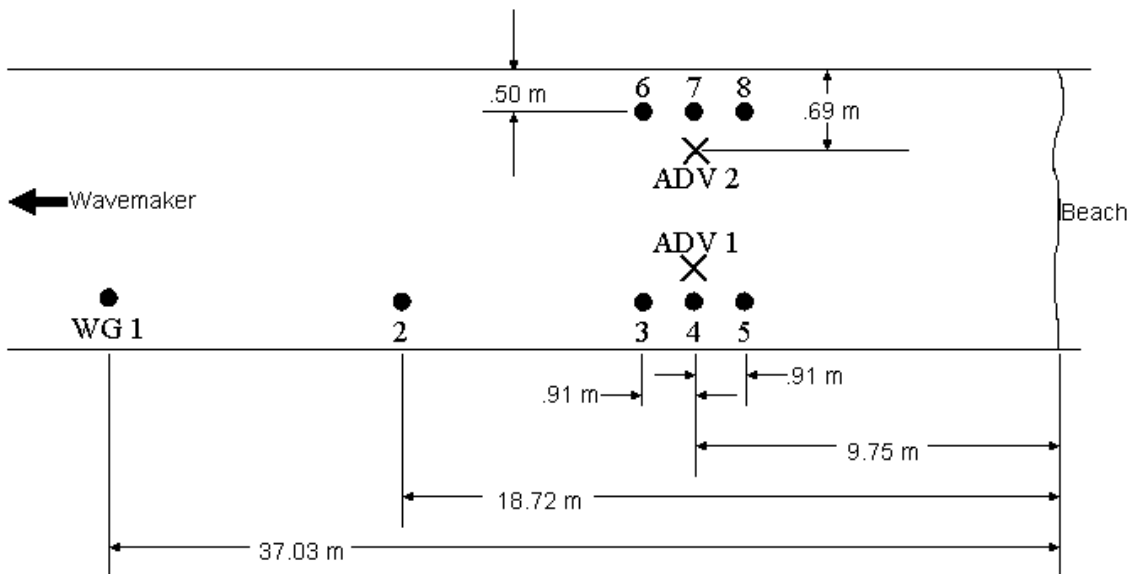


Figure 2: Sensor Location. \times = ADV sample volume. \bullet = Wave gage.

All data were sampled at 50 Hz and filtered at 25 Hz using a 4th order Bessel filter. The filtered data was used in all subsequent analysis.

Fourteen cases of monochromatic waves were generated. Each case was measured for 20 minutes. Depending on wave period, these 20-minute records contain 225-500 monochromatic waves. These fourteen cases represent a broad range of wave conditions, identified in Table 1.

Spilling, spilling/plunging, and plunging breakers were measured in the shoaling region, transition region, and inner surf zone. Figure 3 shows the measurement location for each case, non-dimensionalized by breaking location.

Table 1: Summary of Experimental Conditions

Case	Type	Break. Loc.		Meas. Loc.	ND Meas. Loc.	T (s)	H (m)	L (m)	H0 (m)	L0 (m)	ξ
		x(m)	h(m)								
1.0	P	13.1	1.09	Transition	0.74	4.80	1.04	24.7	1.10	36.0	0.48
1.1	P	12.7	1.05	Transition	0.77	4.80	1.03	24.7	1.09	36.0	0.48
2.0	S/P	13.1	1.09	Transition	0.74	2.80	1.23	11.6	1.31	12.2	0.25
3.0	S	13.7	1.14	Transition	0.71	2.60	1.14	10.2	1.19	10.6	0.25
4.0	P	18.3	1.52	Inner s.z.	0.53	3.90	1.25	19.0	1.36	23.8	0.35
5.0	S/P	21.6	1.80	Inner s.z.	0.45	2.60	1.41	10.2	1.48	10.6	0.22
6.0	S	23.2	1.93	Inner s.z.	0.42	2.55	1.35	9.9	1.41	10.2	0.22
6.1	S	23.2	1.93	Inner s.z.	0.42	2.55	1.35	9.9	1.41	10.2	0.22
7.0	P	4.2	0.35	Shoaling	2.33	5.00	0.44	26.0	0.46	39.0	0.77
8.0	P	4.2	0.35	Shoaling	2.33	3.90	0.49	19.0	0.54	23.8	0.55
9.0	P	6.1	0.51	Shoaling	1.61	2.70	0.63	10.9	0.67	11.4	0.34
9.1	P	2.2	0.18	Shoaling	4.44	2.70	0.39	10.9	0.41	11.4	0.44
9.2	P	2.8	0.24	Shoaling	3.43	2.30	0.32	8.2	0.33	8.3	0.42
11.0	S/P	21.3	1.78	Inner s.z.	0.46	2.60	1.42	10.2	1.49	10.6	0.22

Note:
 - Breaker type based on observed wave breaking
 - Instrument array centered at $x_{meas} = 9.8$ m ($h = 0.81$ m)
 - Non-dimensional measurement location = $x_{meas} / x_{break.loc}$
 - T and H based on offshore wave gage at $x = 37$ m ($h = 3.32$ m)
 - L, H0, L0 computed using linear wave
 - $\xi = \tan(\alpha) / \sqrt{H0/L0}$, $\tan(\alpha) = 1/12$
 - Variance of H ranged from $6.38E-06$ to $6.14E-04$
 - Variance of T ranged from $3.62E-05$ to $4.75E-04$
 - Calculations based on exactly 200 wave

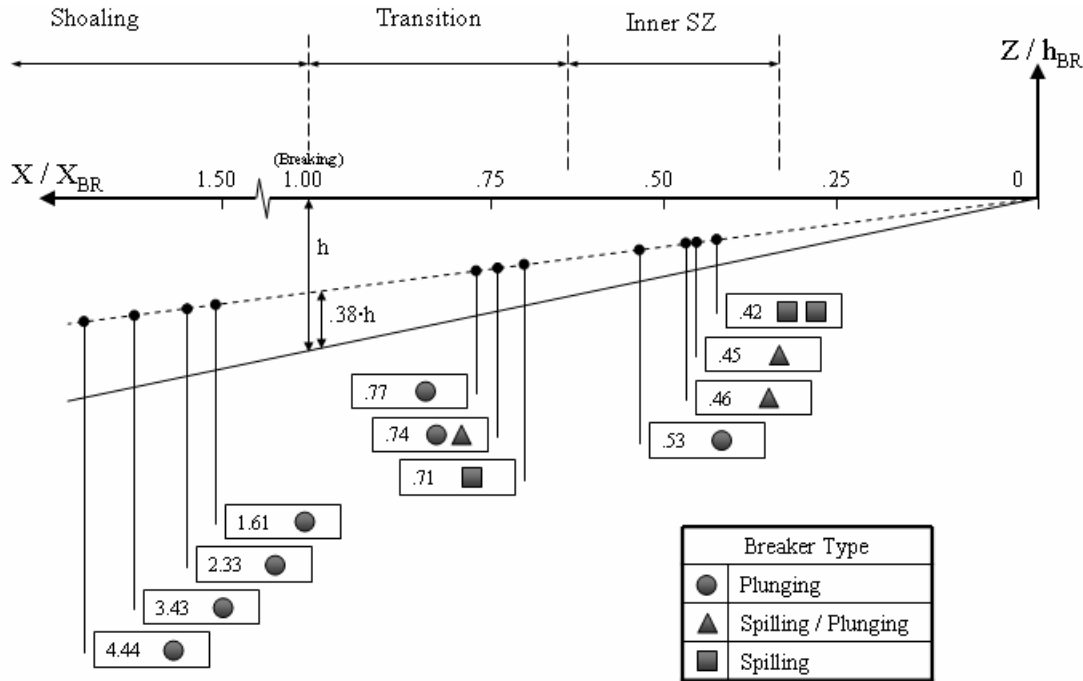


Figure 3: Non-Dimensional Measurement Locations. Three breaker types (P, S/P, S) were measured in three distinct regions (shoaling, transition, inner s.z.). All velocities were measured 38% of the local water depth above bottom.

4. Results

4.1 Data Processing

The ADV's measured velocities ranging from -2.50 m/s to +2.50 m/s. The entrainment of air bubbles in the transition region and inner surf zone occasionally produced “dropouts” in the ADV signal. These anomalies were recorded as velocities of -2.50 m/s or +2.50 m/s. Dropouts were replaced by linear interpolation between viable measurements on either side.

For analysis, the most stable continuous records were used. Stability was based on several considerations. To begin, wave height and period were monitored for consistency. Steady breaking location and breaking uniformity were considered as well. With these factors considered, the most stable continuous 200-wave record in each case was used for analysis.

4.2 General Comparisons

Figures 4 and 5 are representative of the types of results obtained from ensemble averaging and frequency filtering. Frequency filtering was performed with two different cutoff frequencies, $f_c = 10 \cdot f_w$ and $f_c = 20 \cdot f_w$. Estimates using $f_c = 10 \cdot f_w$ are regarded as more accurate.

Most notably, it was found that ensemble averaging produced the largest estimates of turbulence for all cases. Figure 4 shows a typical comparison of the two methods from case 1.0. Both methods clearly identify the large turbulent events that occur at approximately $t/T = 2.5$ and $t/T = 3.5$. However, the ensemble averaging misidentifies certain low-frequency fluctuations as turbulence. At $t/T = 4.5$, a prolonged event lasting approximately one second is identified as turbulence. However, this time scale is too large to be interpreted as turbulence.

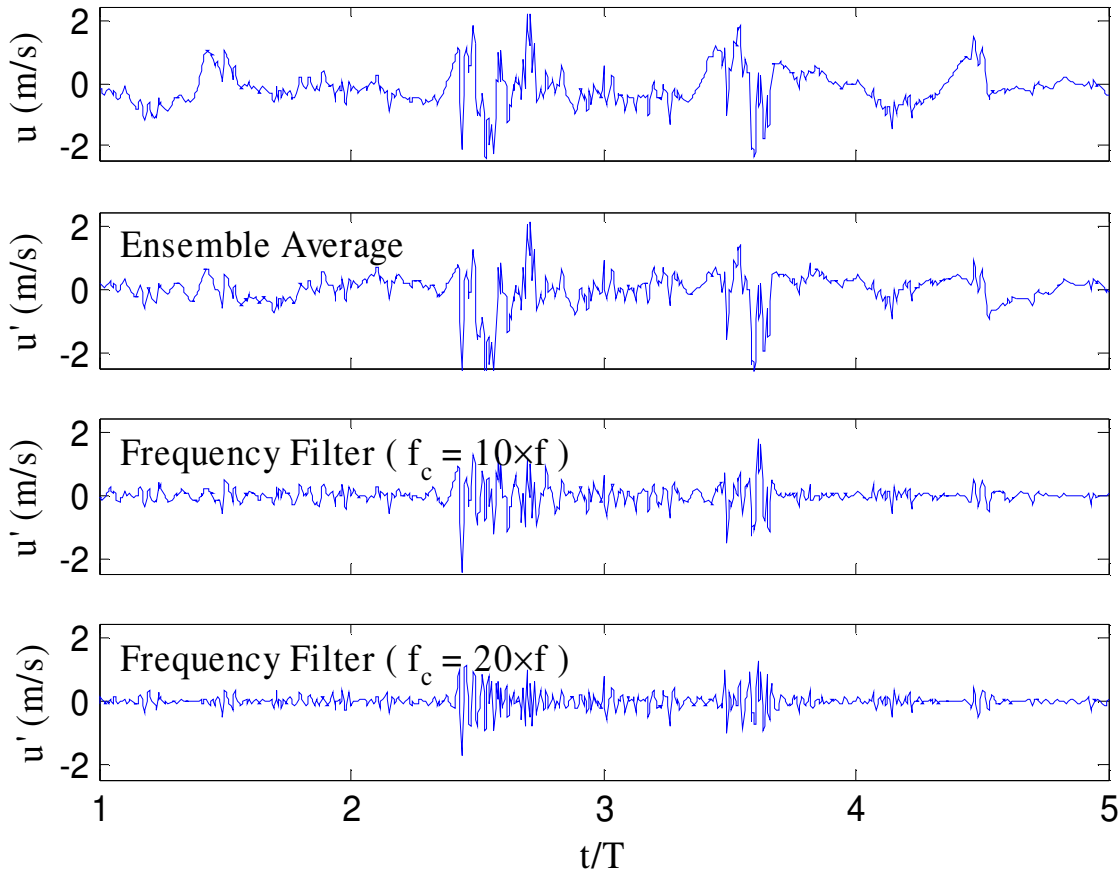


Figure 4: Comparison of u' estimated by ensemble averaging and frequency filtering. Top pane shows the measured velocity. Remaining panes show estimates of u' .

In the same manner that Figure 4 shows estimates of u' , Figure 5 shows estimates of k . As mentioned before, both methods identify the turbulent events at $t/T = 2.5$ and $t/T = 3.5$ seconds. However, ensemble averaging and frequency filtering disagree regarding the magnitudes of these events. This is typical. Ensemble averaging will almost always produce higher estimates for turbulent kinetic energy than frequency filtering at $f_c = 10 \times f_w$. This is due in part to the misidentification of low-frequency motions and irregularities as turbulence.

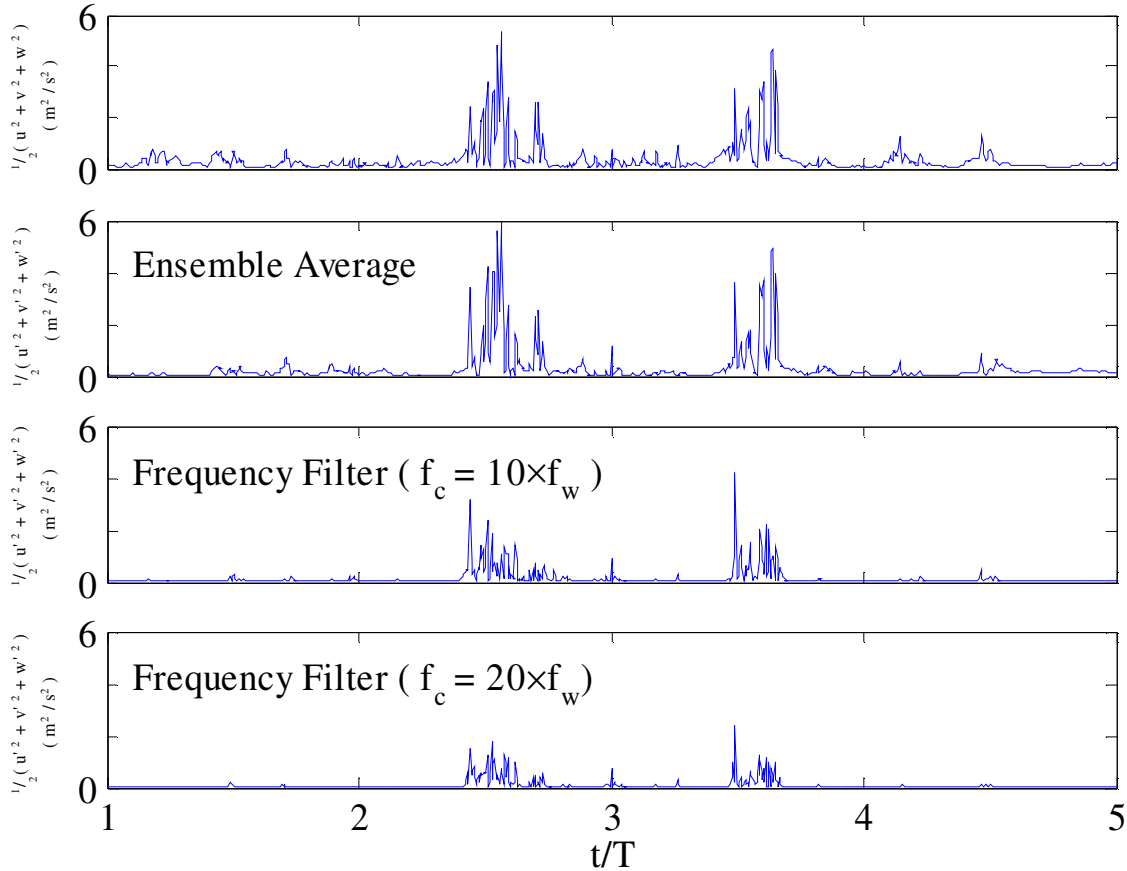


Figure 5: Comparison of k estimated by ensemble averaging and frequency filtering. Top pane shows a measure of kinetic energy, $\frac{1}{2} (u^2 + v^2 + w^2)$. Remaining panes show estimates of turbulent kinetic energy, $k = \frac{1}{2} (u'^2 + v'^2 + w'^2)$.

4.3 Development of Turbulence

We will evaluate the magnitude of cross-shore turbulence as the RMS value of the cross-shore turbulent signal, u'_{rms} . Since waves of different sizes were used at each of the three measurement locations (shoaling region, transition region, inner surf zone), it is necessary to examine u'_{rms} relative to each individual wave case. Therefore, u'_{rms} non-dimensionalized by u_{rms} provides a means to compare relative measures of turbulence from case to case.

As predicted by contemporary knowledge of wave breaking, this value of $u'_{\text{rms}}/u_{\text{rms}}$ increases from shoaling to transition to inner surf zone. Although ensemble averaging and frequency filtering did not produce estimates of equal magnitude, both show the same trend. Turbulence makes up a small portion of the original signal in the shoaling region, before breaking occurs. As the wave breaks, turbulence is quickly developed in the transition region.

By the time the wave enters the inner surf zone, a large amount of the wave energy has been converted to turbulence.

Observing the ensemble averaged u'_{rms}/u_{rms} portion of Figure 6, it is interesting to note that the plunging breaker rapidly develops substantial turbulence in the transition region, but doesn't continue this process into the inner surf zone. This is in contrast to the spilling breaker, which develops turbulence at a slower pace throughout the entire surf zone. This is in agreement with visual observation of breaker types and breaking process studies (Ting, 1994).

In the shoaling region, ensemble averaging consistently estimated u'_{rms}/u_{rms} to be 0.12-0.13, regardless of breaker type. This consistency reflects the supposition that spilling and plunging breakers exhibit minor differences prior to entering the surf zone. Frequency filtered estimates of u'_{rms}/u_{rms} are equally consistent, at 0.04-0.05.

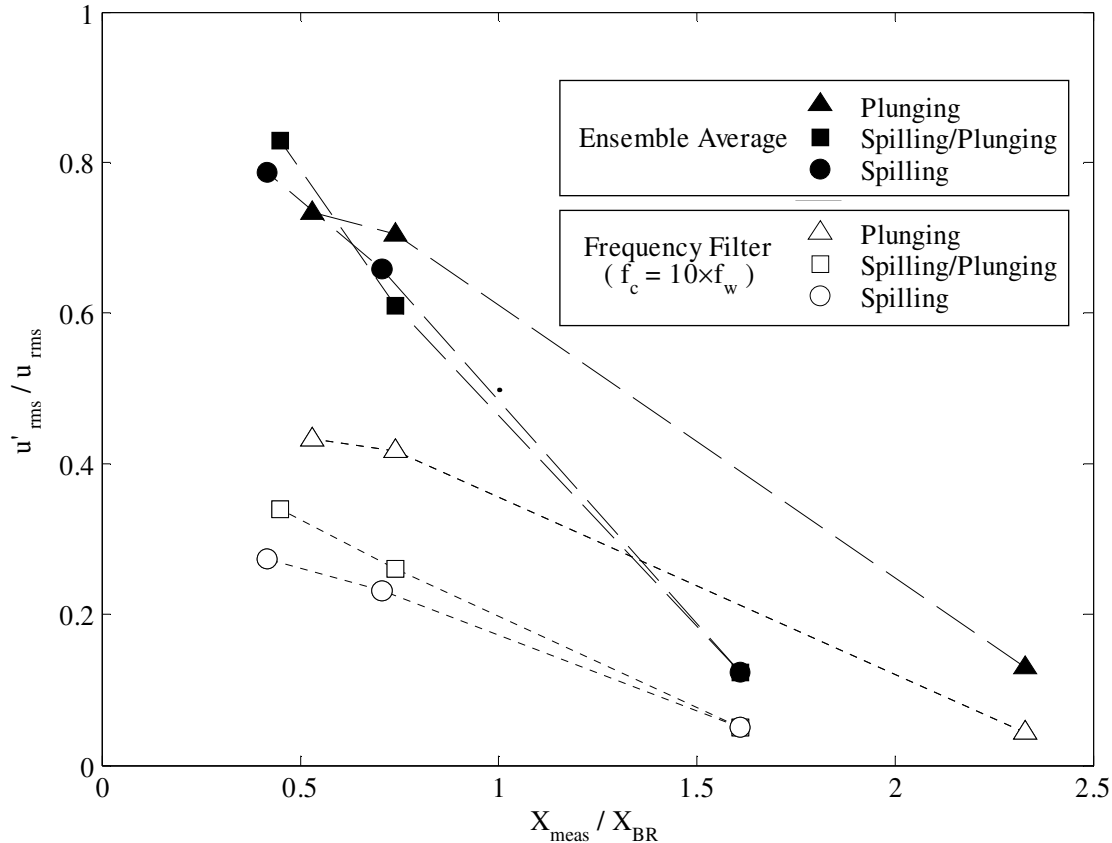


Figure 6: Development of Turbulence. Break point located at $X_{meas}/X_{BR} = 1$. The relative magnitude of turbulence, u'_{rms}/u_{rms} , increases moving shoreward. Also, u'_{rms}/u_{rms} is consistently low in the shoaling region ($X_{meas}/X_{BR} > 1$) for all breaker types.

For direct comparisons, a cutoff frequency of $10*f_w$ will be used, because it is considered to be more practical than a cutoff frequency of $20*f_w$. In general, ensemble averaged estimates of turbulence are approximately twice as large as frequency filtered estimates with $f_c = 10*f_w$. Lowering the cutoff frequency would bring the estimates closer together, but this should be approached with caution.

4.4 Cross-Tank Oscillations

Even if monochromatic waves are generated by the wavemaker, they may not appear monochromatic by the time they reach the sensor area. Minor nonlinearities augment one another as the wave moves down the tank. Visually, the most obvious inconsistency was the cross-tank motion observed in short period wave cases ($T \approx 2.6$ s). A 20-wave portion of case 2 is examined in Figure 7. Definite cross-tank oscillations are present, occurring at extremely low frequencies. Ensemble averaging is wholly unable to account for these oscillations, recording them entirely as turbulence. Frequency filtering with $f_c = 10 \times f_w$ appropriately deals with these obvious non-turbulent motions. It may appear that this cross-tank motion has only minor effects on the estimation of turbulence, affecting only the cross-tank portion of the turbulent signal, v' . However, the cross-tank oscillations create non-uniform breaking conditions, discussed below.

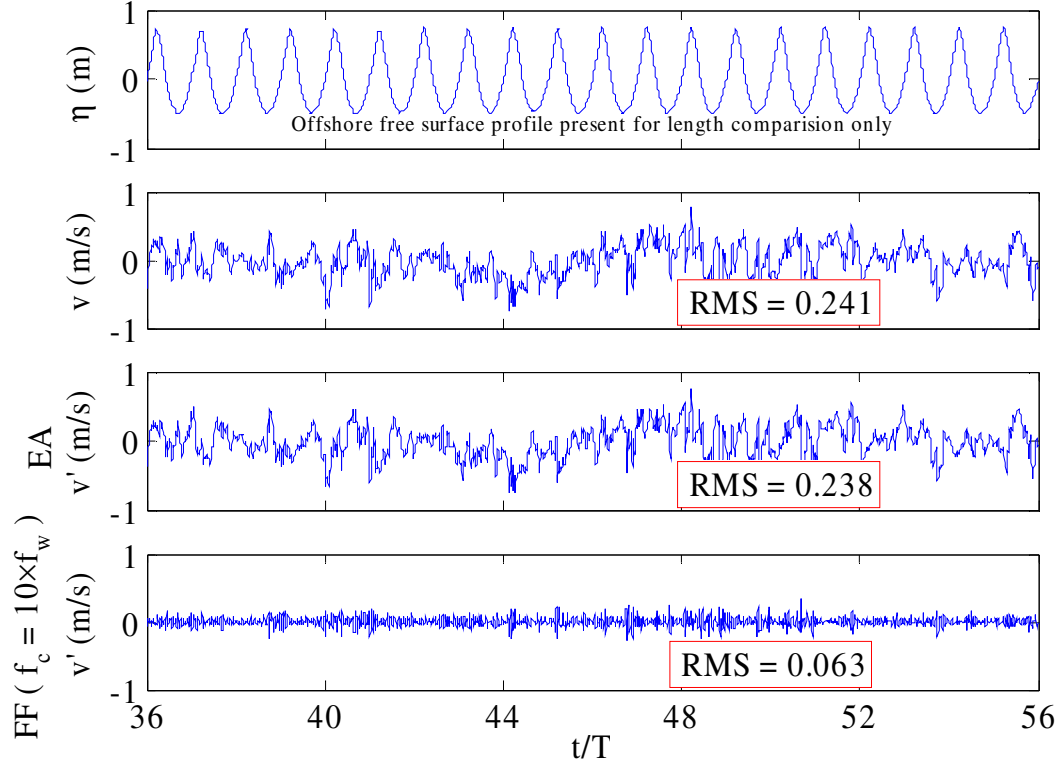


Figure 7: Effect of Cross-Tank Oscillations. Ensemble averaging records low-frequency oscillations as turbulence. Frequency filtering correctly identifies these oscillations as non-turbulent. Note the discrepancies between the v'_{rms} estimates obtained by the two methods.

4.5 Wave Regularity

In the experiment, each case can be ascribed a measure of regularity. Cases 7.0, 8.0, 9.0, 9.1, and 9.2 exhibited the most regularity, with minimal variation in wave properties throughout the record. In contrast, cases 3.0 and 5.0 were semi-irregular. Breaking location and characteristics were not completely constant, with cross-tank motion contributing to these variations. These irregularities are present in both the free surface record and the velocity records. As mentioned before, wave regularity is a critical prerequisite for ensemble averaging. Consequently, ensemble averaged estimates of turbulence for these semi-irregular cases are unrealistically high.

Figures 8 and 9 serve to expose the flaw of ensemble averaging when dealing with semi-irregular waves. For the sole purpose of exposing this flaw, ensemble averaging is compared

with frequency filtering at $f_c = f_w$. It is clear that using a cutoff frequency equal to the wave frequency is highly ineffective at estimating turbulence; the estimates obtained from this frequency filtering will always be high, because low frequency wave motion will be regarded as turbulence.

Figure 8 represents a highly-regular wave. As noted above, frequency filtering with $f_c = f_w$ is entirely incapable of distinguishing turbulence from wave motion. This estimate of turbulence is impossibly high. On the other hand, ensemble averaging is extremely effective.

Figure 9 applies the same test to a semi-irregular wave case, which was riddled with large, low frequency oscillations and non-uniform breaking. Again, frequency filtering with $f_c = f_w$ is not able to identify all non-turbulent motions, giving an impractically high estimate of turbulence. Unfortunately, the estimate from ensemble averaging is not any better. In fact, for this 14 wave record, the frequency filtered $u'_{rms} = 0.38$, while the ensemble averaged $u'_{rms} = 0.46$ (ensemble average based on entire 200-wave record). Based on the solid postulation that frequency filtering with $f_c = f_w$ will always overestimate turbulence, having ensemble averaging exceed this estimate raises serious concerns.

The main reason for the unreasonable ensemble averaged estimate of u' lies in the large low-frequency oscillations, which are most likely evidence of sieching. For the experiment, the wavemaker's active wave absorption system was not operating. Consequently, wave reflection along the length of the tank is visible in free surface records and velocity records. This caused breaking characteristics to change throughout the record.

Even slight irregularities push ensemble averaged estimates of turbulence remarkably high. For studies using ensemble averaging, wave parameters should be modified to reduce non-linear motion and achieve more regular breaking conditions.

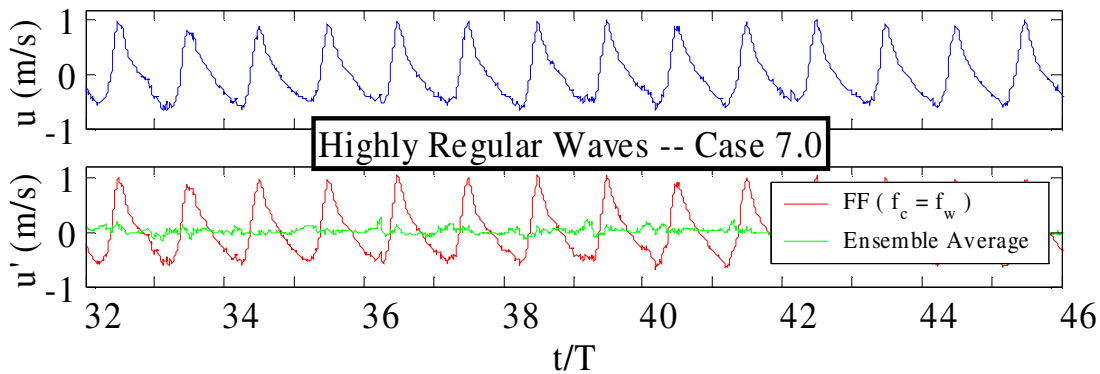


Figure 8: Estimates from Regular Waves. Ensemble averaging estimates u' well.

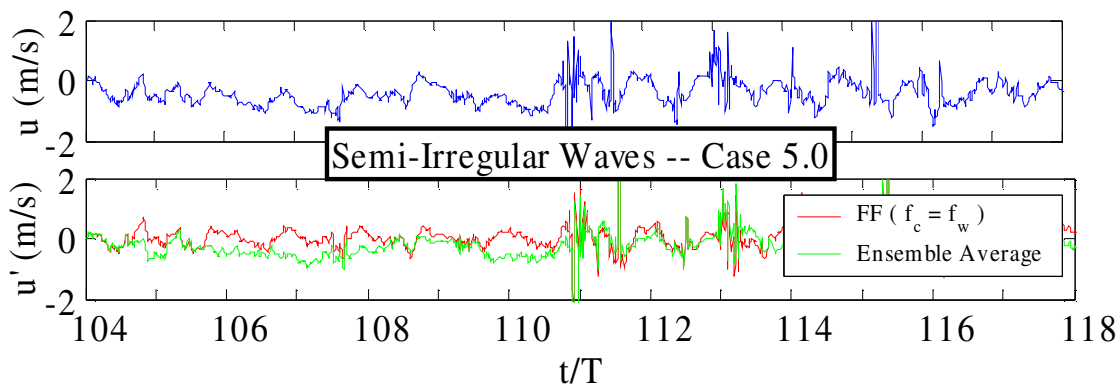


Figure 9: Estimates from Semi-Irregular Waves. Ensemble averaged estimate is flawed.

4.6 Breaker Type

Ensemble averaging produced larger estimates of turbulence than frequency filtering ($f_c = 10*f_w$) for every case. It is instructive to determine the conditions for which the two methods produced similar estimates. A good comparison of the two methods is the ratio $u'_{rms}(FF) / u'_{rms}(EA)$, where FF indicates the use of frequency filtering at $f_c = 10*f_w$ and (EA) indicates the use of ensemble averaging. Similar ratios can be defined with k and turbulent shear stress, $u'w'$. Figure 10 plots these ratios based on breaker type and measurement location. It is clear that breaker type has a large effect on the relative amounts of turbulence detected by each method. The two methods agree most closely for plunging breakers, and spilling breakers show more of a discrepancy between the two methods. Also, from Figure 10, note that measurement location has minimal effect on the ratio of turbulence detected by the two methods. Breaker type is the primary factor that determines how similar the two estimates are.

With no absolutely reliable measure of turbulence to compare these estimates with, it becomes necessary to draw conclusions based primarily on a comparison of the two methods. There could be numerous explanations why the methods agree less for spilling breakers than plunging breakers. This could be due to the fact that for this experiment, spilling breakers were less regular than plunging breakers. The spilling breakers (cases 3.0, 6.0, and 6.1) had periods of 2.55-2.6 seconds, which incited the cross-tank motions described above. This resulted in uneven and inconsistent breaking. As previously mentioned, irregular wave breaking inflates ensemble averaged estimates of turbulence.

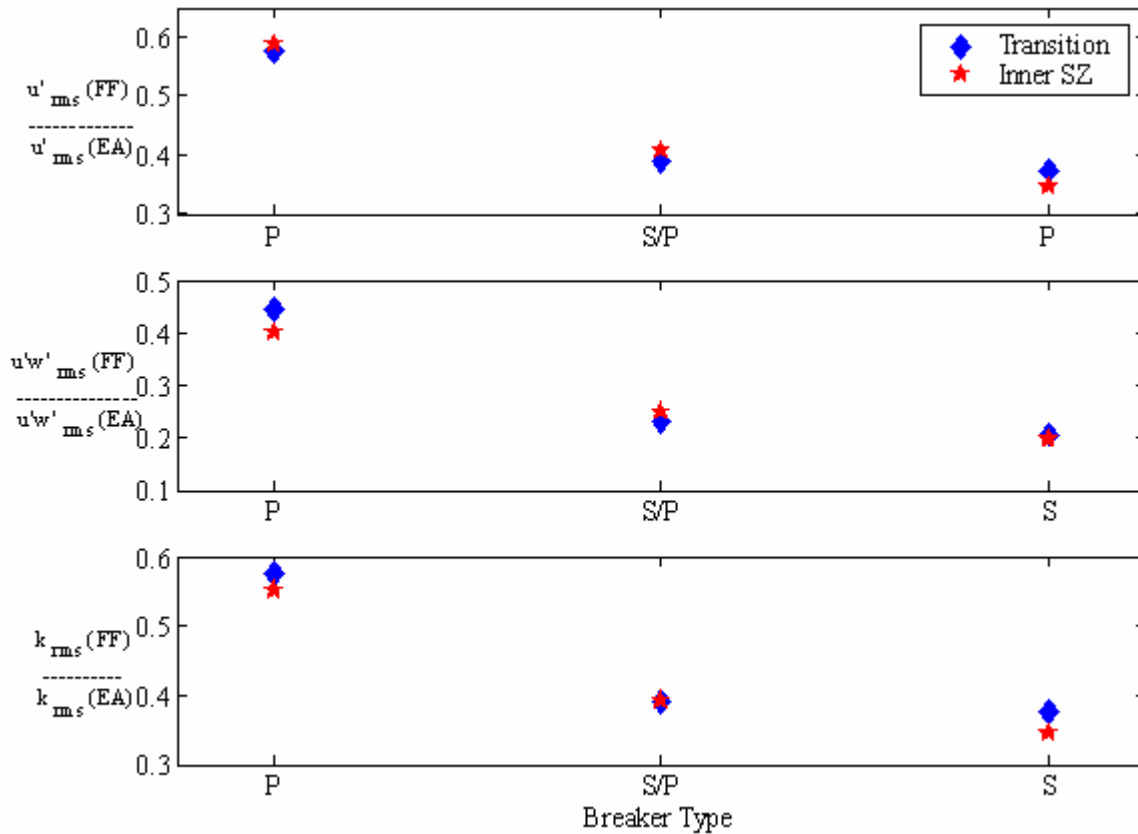


Figure 10: Effect of Breaker Type. Ensemble average and frequency filter produce most similar results when applied to plunging breakers. Note: frequency filtering performed with $f_c = 10*f_w$.

5. Conclusion

A laboratory experiment was conducted to compare methods of estimating turbulence. This paper compares the two most common methods, ensemble averaging and frequency filtering. Due to the absence of absolute measurements of turbulence, these methods were primarily compared against one another.

It was shown that ensemble averaging will produce reasonable estimates of turbulence when applied to highly regular waves. However, when even slight irregularities are present, estimates are biased high. Therefore, when applying ensemble averaging to obtain estimates of turbulence, it is necessary to assess regularity of the waves. Low frequency cross-tank motion and sieching should be identified as well. Any of these irregularities will influence and estimate of turbulence. If conditions stray far from stereotypical monochromatic uniform waves, ensemble averaging should be used with awareness of the tendency toward overestimation.

Frequency filtering is highly adept at dealing with irregularities. For waves that do not fit ensemble averaging criteria, frequency filtering appears to provide decent estimates of turbulence. However, additional research focusing on appropriate cutoff frequencies is considered necessary. For this study, $f_c = 10 \cdot f_w$ excluded some low frequency turbulent motions. A lower cutoff frequency would be desirable for further comparisons. Also, determining cutoff frequencies based on turbulent length scales should be attempted (Nadaoka, 1982).

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Biography

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