Measurements of Free Surface Turbulence

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Free-surface turbulence is important to the transfer of heat and mass across an air-liquid interface. In the absence of wind shear and surface waves, turbulence generated below the water surface (as from a streambed) is one of the controlling factors in air-water mass transfer. Research has shown that the temporal fluctuations in the two-dimensional divergence of the surface velocity field are related to the liquid-film mass transfer coefficient. To aid in understanding the relationship between free-surface turbulence and mass transport, an oscillating grid chamber has been used to study turbulence at a water surface. A horizontal grid of square bars was oscillated vertically beneath the water surface. Turbulence generated by the grid propagates up towards the water surface, generating near-two dimensional turbulence right on the free surface. Particle Image Velocimetry (PIV) was used to measure the temporally varying flow pattern on the water surface for three different energy levels in the chamber. Data were recorded over eight different sub-regions of the water surface, and the velocity, vorticity, and two-dimensional divergence were calculated as functions of space and time for each region. The spatial variations in two-dimensional divergence are shown to be similar to those found in flume experiments; this suggests that that the oscillating grid chamber may be used as a direct analogue to open-channel flows for studying interfacial transport phenomena.

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INTRODUCTION

Turbulence on the surface of free liquid flows is of importance in the transfer of heat and mass across the liquid-atmospheric interface. Reaeration in streams, mixing in water and wastewater treatment processes, and other natural and engineered processes rely on transfer of mass from one phase to another across such a surface. These transport processes are controlled by both gas- and liquid-film transfer coefficients; for slightly soluble compounds such as oxygen, the transfer rate is dominated by the liquid-side mass transfer coefficient [*Jahne and Haubecker*, 1998]. The liquid-film coefficient in turn is related to features of the flow, in particular the turbulence structure right at the interface [*Gulliver and Tamburrino*, 1995]. In many cases (such as open channel flows free from wind shear), the turbulence is generated well below the liquid surface (*e.g.* at the stream bed or channel bottom) and propagates upwards towards the air-liquid interface.

The present study investigates the turbulence on the free-surface of water in an oscillating grid tank. The tank was constructed for studies of chemical fluxes from sediments to water and from water to the atmosphere. Details of the construction and quantification of bulk turbulence parameters using Laser Doppler Velocimetry, as well as measurements of the oxygen mass transfer coefficient using this device are described elsewhere [*Orlins*, 1999].

The turbulence on the free liquid surface was investigated using Particle Image Velocimetry. In this paper, we will discuss the experimental aspects and data reduction, examine results from the present study, and conclude with a comparison between free-surface turbulence generated with this device and that from other flumes and grid-stirred tanks reported in the literature.

EXPERIMENTAL ASPECTS

Oscillating Grid Chamber

An oscillating grid is often utilized to approach horizontally homogeneous turbulence in a small chamber. The oscillating-grid chamber has been used as a more convenient substitute for flumes and tanks, especially when investigating the transport of potentially toxic substances [*Connolly, et al.*, 1983; *Valsaraj, et al.*, 1997]. The turbulence characteristics in the bulk of the fluid have been well characterized [*e.g., Hopfinger and Toly*, 1976; *Thompson and Turner*, 1975], but the turbulence at the water surface has not previously been measured.

Since there is no mean shear in the oscillating grid mixing chamber, the total kinetic energy (TKE) of the turbulence can be used as a measure of the energy in the system. The TKE can be defined from the r.m.s. velocity fluctuations:

$$TKE = \tfrac{1}{2}\left(u'^2 + v'^2 + w'^2\right) \qquad (1)$$

For a grid with square bars, it has been shown [*e.g., Hopfinger and Toly*, 1976; *DeSilva and Fernando*, 1992] that the horizontal (u', v') and vertical (w') r.m.s. fluctuations in the bulk of the fluid can be described by:

$$\begin{aligned} u' &= \sqrt{\overline{u^2}} = C_1 M^{0.5} S^{1.5} f z^{-1} \\ w' &= \sqrt{\overline{w^2}} = C_2 M^{0.5} S^{1.5} f z^{-1} \end{aligned} \qquad (2)$$

where S is the stroke length, f is the oscillation frequency, z is the distance away from a virtual origin, M is the mesh spacing of the grid, and C_1 and C_2 are constants that may depend on the geometric parameters of the grid. Here, u and w are the instantaneous velocity fluctuations ($u = U - \overline{U}$; $w = W - \overline{W}$, where U and W are the instantaneous velocities and the overbars denote the mean values). Hopfinger and Toly report values of C_1 and C_2 of approximately 0.25 and 0.27, while DeSilva and Fernando measured values of approximately 0.22 and 0.26, respectively.

For the present work, experiments were conducted in a square chamber 50 cm on a side, with a horizontal 7x7 grid of 12 mm square bars spaced 62.5 mm apart. The grid was connected by a vertical shaft and eccentric drive to a variable-speed DC motor with a programmable speed controller. A stationary sleeve mounted to the lid of the tank surrounded the vertical drive shaft and projected below the water surface, to minimize surface waves caused by the motion of the shaft. The grid stroke length could be varied from 2 to 4 cm, and the vertical oscillation frequency maintained in the range 3 to 7 Hz.

For the tests described here, the water depth was 30.6 cm, the grid centerline elevation was 16.6 cm from the tank bottom, the stroke length was kept constant at 3 cm, and the oscillation frequency was set to 3, 5, or 7 Hz, depending on the test. The corresponding total kinetic energy of turbulence (TKE) calculated using Equation (1) near the water surface could thus be varied from about 0.7 to 4.0 cm^2/sec^2.

Particle Image Velocimetry System

The turbulence right on the water surface was measured using Particle Image Velocimetry (PIV), as shown schematically in Figure 1. A commercial Hi-8 video camcorder was used to record the motions of polystyrene particles floating on the water surface for different turbulence conditions in the tank. By recording the particle motions over relatively long times (1-5 minutes), both the spatial and temporal nature of the free-surface turbulence could be investigated.

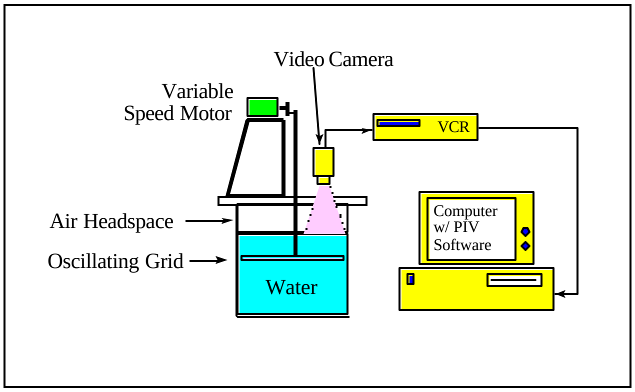

Figure 1. Experimental Setup.

Image capture system. The camera field of view was set to span approximately 18 cm to obtain the required resolution for capturing the small eddies using the PIV technique. To ascertain the spatial variations in free-surface turbulence within the tank, eight separate sub-areas of the water surface were recorded to provide overlapping coverage of the full width of the tank. Five minutes of the free-surface motions were recorded for each grid oscillation frequency at each of the eight measurement locations. The camera recorded images at a nominal rate of 30 frames per second, resulting in a total of approximately 9000 images that could be digitized for analysis.

Velocity field calculations. The resulting video images were digitized using a computer-based frame-grabber and stored as 8-bit grayscale image files with 640x480 pixels. Image scaling was determined by floating a ruler on the water surface, and determining the number of pixels spanned by a given distance.

The free-surface velocity was calculated from pairs of images using a commercial PIV analysis program (INSIGHT-NT, by TSI, St. Paul, MN) with a cross-correlation algorithm. The spot size for flow field interrogation was 32x32 pixels, with a 50% overlap between analysis spots. This resulted in approximately 26 rows x 38 columns of vectors for each image, depending on the size of the actual image analysis area used. For each operating condition and camera location, velocity fields were calculated for 1800-2100 image pairs (60 to 70 seconds), providing a spatial and temporal record of the free surface motions. Program output consisted of horizontal and vertical pixel displacements for each analysis spot.

Preliminary analysis of the surface flow patterns indicated that the velocities over much of the tank were relatively low, ranging from about 3 to 23 mm/s. In order to distinguish particle motions using the PIV technique, it is best when particles move at least one pixel between the digitized images. In addition, to minimize the number of "lost pairs" between images, the maximum pixel displacement should be less than ¼ of the spot size [*Keane and Adrian*, 1990; 1993]. To achieve these ranges of pixel displacements, the cross-correlation was performed between every third image, with a resulting time differential of 3/30 or 0.1 seconds. Processing was done on all video frames in the sequence, and the resulting 0.1 second displacement fields were interleaved to synthesize a "smoothed" 30 Hz data set. The interleaving was achieved by computing the velocity field between every third frame, without skipping any frames. For example, the first velocity field would be calculated between frames 1 and 4; the second between frames 2 and 5, the third between frames 3 and 6, the fourth between frames 4 and 7, and so on.

Post-processing of velocity files. PIV vector validation was done with a shareware post-processing program. Spurious vectors were removed and vacant vector regions were filled using the program CLEANVEC [*Soloff and Meinhart*, 1999] from the Laboratory for Turbulence and Complex Flow at the University of Illinois at Urbana-Champaign.

The resulting "cleaned" vector files were then converted to engineering units (coordinates ? mm, pixel displacements ? velocities in mm/s), and the velocity variance (*i.e.*, measurement uncertainty) was calculated for each vector. After the raw pixel displacements were converted to engineering units, the vector fields were then smoothed using a 3x3 (Gaussian) weighting matrix.

The two-dimensional vector flow field on the water surface was used to calculate the vorticity and two-dimensional divergence of the flow field over space and time. The vorticity and two-dimensional divergence of the flow field were calculated using central differences.

Power spectra of velocity and divergence at 9 points in each of the eight imaging regions were calculated from the time series data sets, and then ensemble averaged to create a representative power spectrum for each operating condition.

RESULTS AND DISCUSSION

Qualitative Flow Field Characterization

A sample of the results is shown in Fig. 2, which gives typical velocity, vorticity, and 2-D divergence for a grid oscillation frequency of 5 Hz. These measurements are shown for two instants, with a temporal difference of 0.1 seconds.

The velocity field on the water surface was well developed, changing gradually over time and space. Local velocities ranged from near-zero to over 20 centimeters per second, depending on the grid oscillation frequency and the location in the tank. For a grid oscillation frequency of 3 Hz, the peak surface velocity was about 8 cm/second. The average magnitude of the surface velocity increased at a grid oscillation frequency of 5 Hz, with regions of "hot spots" or intense rapid surface movement associated with upwelling of fluid from the bulk, as shown in Fig. 2. At a grid oscillation frequency of 7 Hz, the surface flow patterns were much

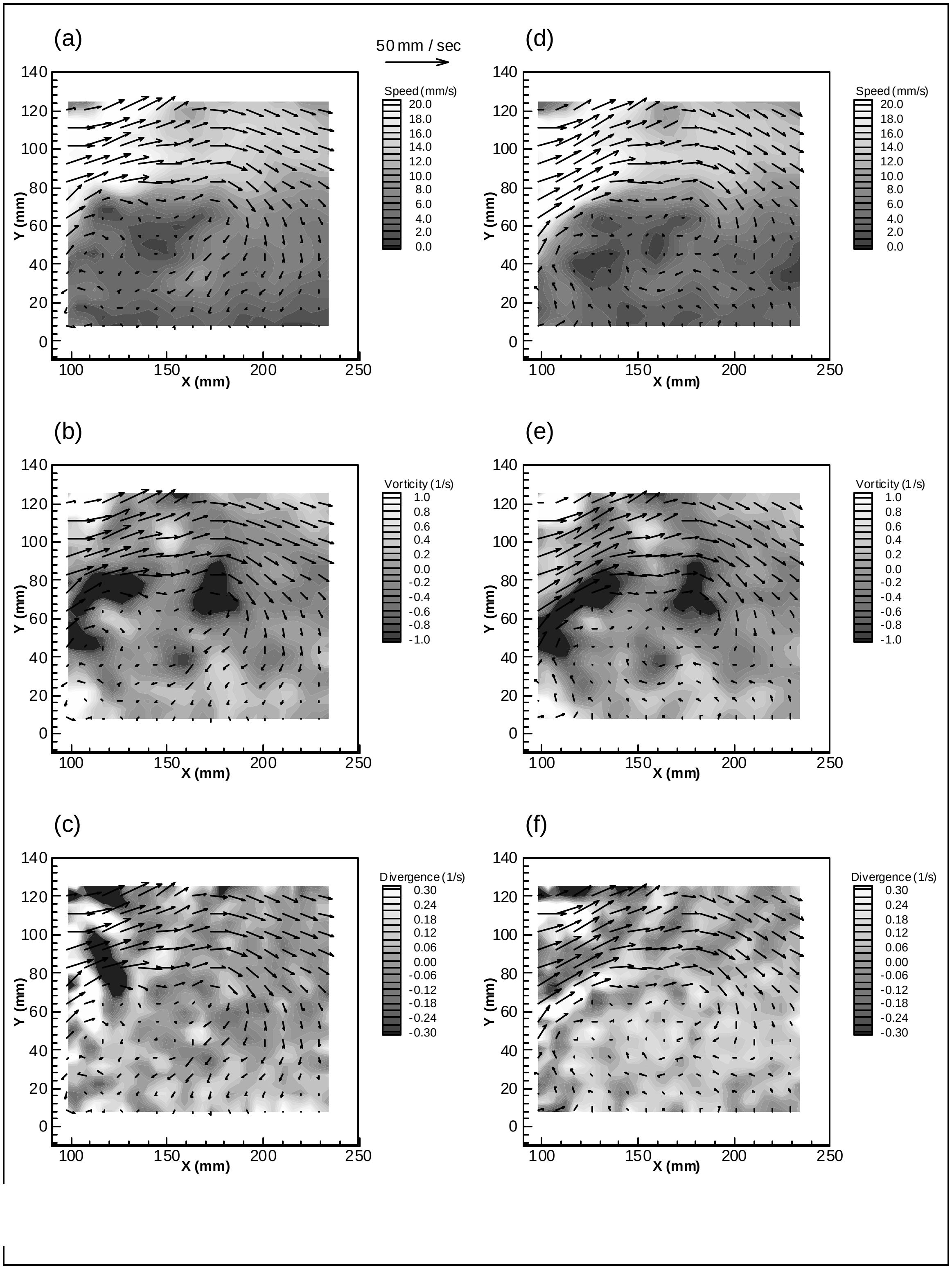

Figure 2. Typical velocity, vorticity, and divergence for grid oscillation frequency of 5 Hz. (a) – (c): time = t; (d) – (f): time = t + 0.1 second.

more active, with strong circulation patterns over some image regions and areas of little surface movement in others.

Eddies form and disappear on the free surface and persist in stable forms for relatively long periods of time. The vorticity field evolves relatively slowly over time (tens of seconds), with spatial scales on the order of 2 cm for the smaller eddies and 10 cm for the larger ones.

There is little variation in vorticity over a time span of 0.1 seconds, as shown in Figures 2b and 2e. However, the vorticity field does undergo substantial temporal changes as the eddies appear, evolve, migrate, and disappear over longer time periods. It appears that eddies first form in the corner regions of the tank for small energy inputs (*i.e.* low oscillation frequencies). As the grid frequency is increased, these vortex structures increase in size and magnitude, and additional regions of high vorticity form near the sides and then near the center of the chamber. At the highest energy level investigated (grid frequency of 7 Hz), the regions of large vorticity magnitude appear evenly distributed over the water surface of the tank.

The two-dimensional divergence (Figs. 2c and 2f) has both spatial and temporal scales much smaller than the large-flow features such as vorticity. The length scale of the finer features is on the order of 1 cm. The temporal variations are rapid, with the divergence changing often, at frequencies approaching the image capture rate. The spatial distribution of divergence is qualitatively quite similar to that measured in open channel flows [*Tamburrino*, 1994; *Kumar, et al*., 1998].

Spectral Analysis

For each of the eight image analysis regions, time series data were extracted at nine locations from the measured flow field. Frequency spectra of the U-component of velocity and divergence were computed for each of these 72 locations, and then averaged to create an overall spectrum for each of the three grid oscillation frequencies tested.

The frequency spectra of free-surface velocity are given in Fig. 3. Spectral peaks and noise in a "bias region" at and near the grid oscillation frequencies have been removed for clarity. These curves seem to indicate a slope of –2 on a log-log plot in the frequency decade above that of the peak values. This is so consistent that we believe it may have some relevance for free-surface flows.

Comparisons were made with the velocity spectra in the bulk of the flow, as shown in Figure 4 for a 5 Hz grid oscillation frequency. The spectra of free-surface velocities have a magnitude that is approximately a factor of $10^{3.5}$ lower than the spectra in the bulk flow. This seems to indicate that there is significant dissipation of turbulence as the free surface is approached. In addition, while the bulk flow spectra follow a slope of –5/3 between 1 and 40 Hz, corresponding to the inertial subrange, the spectra on the water surface follows a slope of –2 between 0.1 and 5 Hz.

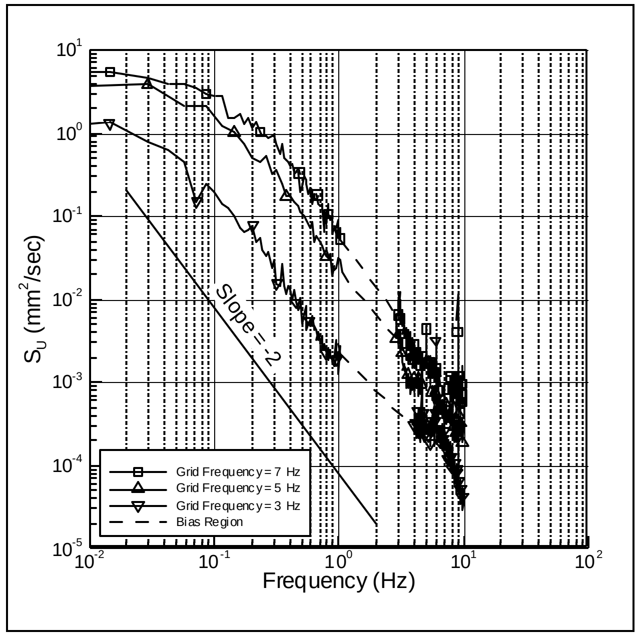

Figure 3. Frequency spectra of horizontal velocity component.

It is interesting to make a comment regarding the slope of the velocity spectra. In three-dimensional turbulence, a –5/3 slope is representative of the inertial sub-range. However, this is not the case here because close to the free surface, the motion is restricted in the vertical direction and the flow becomes more two-dimensional. For two-dimensional turbulence, the inertial sub-range is characterized by a proportionality to ?$^{-3}$ [*Batchelor*, 1969]. A dependency on ?$^{-5/3}$ has been detected in the productive sub-range [*Farge*, 1992]. There is, however, little turbulence production at a free-surface with no wind, and we are well below the frequency of the inertial sub-range. Thus, these spectra represent neither the production of turbulence nor the inertial sub-range.

The –3 slope of the inertial subrange for free-surface turbulence seems to occur above a frequency of 5 Hz. There are few studies of free-surface turbulence to compare with these results. Brumley and Jirka (1987), however, used rotating hot-film probes to measure the turbulence below but near the free surface in a grid-stirred tank. In their work, a moving probe was used to measure a turbulence field that was varying in both space and time. Brumley and Jirka calculated spatial power spectra from their velocity measurements. Their results have been normalized and are based on wave number, so it is difficult to make direct comparisons to the present study, but qualitative comparisons can be made.

In Brumley and Jirka's work, the turbulence spectra in the bulk of the flow follow a –5/3 slope. As the free surface is approached, a pattern develops in the free-surface velocity spectra with a slope of –3 at the higher frequencies and a slope of –2 at the lower frequencies, similar to what is seen in Fig. 4. Since there is no production of turbulence at the free-surface in these flows, we believe that the –2 slope is related to the stretching of turbulent eddies from 3-dimensional into 2-dimensional forms.

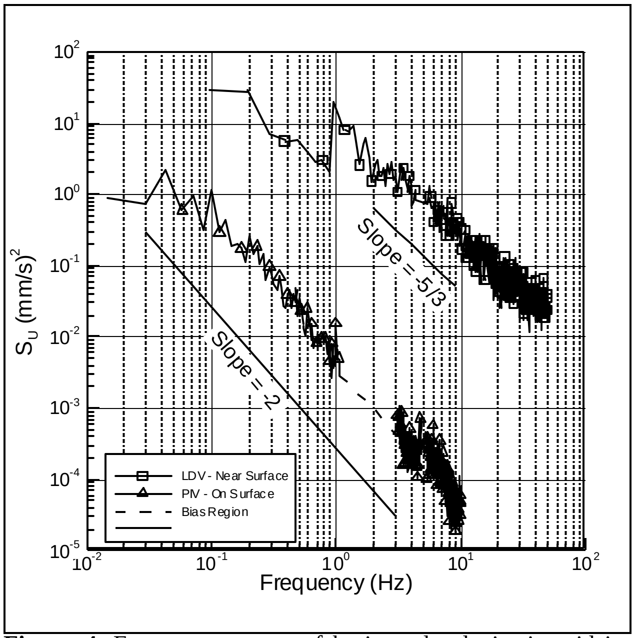

Figure 4. Frequency spectra of horizontal velocity in grid in grid-stirred tank. Top curve: measured with LDV, below water surface. Bottom curve: measured with PIV on water surface.

The spectra of 2-D divergence (?w/?z) were also computed, as shown in Fig. 5. The spectra follow a slope of –1 until a low-frequency plateau is reached, similar to the spectra of McCready, *et al*. (1986).

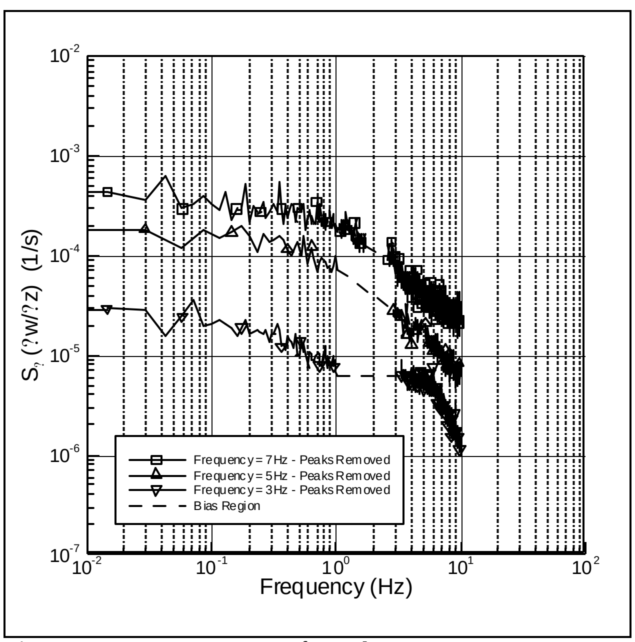

Figure 5. Frequency spectra of 2-D divergence.

CONCLUSIONS

Measurements made of free-surface turbulence in an oscillating grid chamber were made using Particle Image Velocimetry. The results were compared with prior studies of turbulence below the free surface in oscillating grid tanks. Turbulence intensity increases with increasing grid oscillation frequency, as do surface velocity, vorticity, and two-dimensional divergence. The velocity and calculated vorticity change slowly over time and space, while the divergence fluctuates more rapidly and over a smaller spatial scale. The velocity spectra at the water surface decays in the inertial range more rapidly than in the bulk, which is in agreement with measurements made by Brumley and Jirka (1987) just below the free surface. The predominant slope of the spectra was –2. At higher frequencies, the slope was –3, which corresponds to the dissipation range for free-surface turbulence.

The spatial variability of 2-D divergence in the grid-stirred tank is strikingly similar to that found from Kumar, *et al.'s* (1998) measurements in a laboratory flume, and the spectra of 2-D divergence are similar to those obtained by McCready, *et al*. (1986). Since both heat- and mass-transfer across the air-water interface are related to the spectrum of 2-D divergence, this suggests that the oscillating grid chamber may be appropriate as a direct analogue to open-channel flows for studying interfacial transport phenomena. Identification of the relationship between free-surface turbulence in an open channel flow and surface renewal rate in open-channel flows and stirred chambers will allow more detailed investigations of mass transfer in the future.

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