LABORATORY EXPERIMENTS ON TURBULENT TRANSITION IN THE BOTTOM BOUNDARY LAYER UNDER IRREGULAR WAVES

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Characteristic behaviors of turbulent transition in the bottom boundary layer under irregular waves have been studied from laboratory data. It has been observed that flow transition under irregular waves is not only governed by instantaneous flow properties but also depends on the conditions in the preceding waves. While laminar-to-turbulent transition required a build-up of turbulent energy sufficient enough to produce traces of turbulence, for turbulent-to-laminar transition the turbulent wave was required to be followed by several successive smaller waves to allow total dissipation of turbulent energy. As a result waves with much higher Reynolds numbers show predominantly laminar properties, whereas, wave with Reynolds number as small as $5.0\text{x}10^3$ shows turbulent behavior. Use of conventional wave friction factor diagram, therefore, becomes unsuited to indicate flow transition under irregular waves. Also transition takes place over a much wider range of wave Reynolds number than observed for regular waves.

Key words: *irregular waves, bottom boundary layer, turbulent transition*

1. INTORDUCTION

One of the most important factor determining the vertical velocity distribution under waves is whether the flow is laminar or turbulent. Consequently there have been many studies to determine the condition under which transition takes place.

Transition first starts at decelerating phases prior to flow reversal. This is due to that with increasing free stream velocity the adverse pressure gradient becomes relatively large and the near wall velocity becomes relatively small leading to a favorable environment for initiation of turbulence. Some researchers (Foster et al., 1994) have also suggested that the initiation of turbulence is because of shear instability of the velocity profile.

A precise identification of flow condition at which turbulent traces starts to appear is rather difficult because of its highly stochastic nature, and also as it is dependant on individual experimental environments. However, several researchers have put forward wave Reynolds numbers (*Re*) at which turbulence first appeared (Hino et al., 1976; Jensen et al., 1989; Eckmann and Grotberg, 1991; Akhavan et al., 1991; Verzicco and Vittori, 1996 etc.).

Flow conditions varies over a wide range under irregular waves within a wave terrain. While some larger waves show turbulent behavior, there also exists smaller waves where flow is essentially laminar. Wave irregularity thus introduces a wide range of pressure gradient condition which subsequently influences the transitional behavior. Considering that natural waves are irregular and that vertical velocity distribution governs the bed movement, it is important that transitional characters are investigated under irregular waves.

In the present paper flow transitional behavior has been investigated from laboratory data. Data from velocity measurements in the boundary layer has been analyzed to study flow transition and to investigate the influence wave irregularity has on flow transition. The results show that the transition under irregular waves is not only governed by instantaneous flow properties, but also dependant on flow situations in preceding waves. This 'history effect' causes much higher waves to remain in laminar regime and waves with much smaller Reynolds numbers to show turbulent behavior.

2. LABORATORY DATA

(1) Instrumental Set-up

The principle of the experimental system has been based on utilizing a servo-motor at the core. The input piston signals, pre-obtained from generated irregular waves, have been applied to drive the servo-motor. Flow measurements then have been performed in a wind tunnel connected through a piston system. As such the experimental system consists of two major components, a wave generation unit and a flow measuring unit.

The wave generation unit is made up of signal control and processing components along with piston mechanism. The piston displacement signal has been fed into the instrument through a PC. Input digital signal has been converted to corresponding analog data through a digital-analog (DA) converter. The analog signal drives the servo motor connected through a servo motor driver. The piston mechanism has been mounted on a screw bar which again was connected to the servo motor. The feed-back on piston displacement, from one instant to the next, has been obtained through a potentiometer that compared the position of the piston at every instant to that of the input signal, and subsequently adjusted the servo-motor driver for position at the next instant. A smooth piston movement has been ensured repeating the process until the end of the input signal has been reached. A schematic diagram of experimental set-up is shown in Fig.1.

The flow measurement unit comprises of a wind tunnel and a one-component laser Doppler velocimeter (LDV) for flow measurement. The piston system has been connected to the wind tunnel through PVC pipes. The wind tunnel is 5m long, 20cm wide and 10cm high and was constructed from mirror-plane PVC plates on all four sides. Near the measuring section the side walls of the wind tunnel were made of transparent fiber-glass sheets to facilitate LDV measurements (Fig.1).

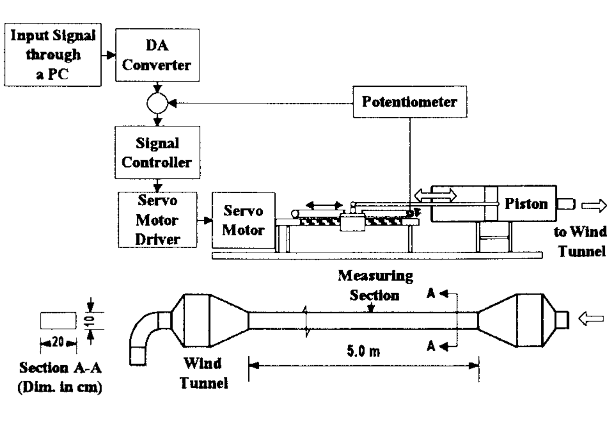

Fig.1: Schematic diagram of experimental set-up

(2) Experimental Conditions

Experiments have been carried out for two transitional and turbulent cases. The experimental conditions are presented in Table 1, where $Re_{1/3}= U_{1/3}^2/(\omega_{1/3}\nu)$ is wave Reynolds number based on significant velocity, $U_{1/3}$, and wave frequency, $\omega_{1/3}$ ($=2\pi/T_{1/3}$, $T_{1/3}$ being significant wave period). ν and ρ are kinematic viscosity and mass density of air. A portion of analysis results for Case 1 has been presented by Samad et al. (1999). However, in this paper additional features for Case 1 have been considered in support of the finding from Case 2.

For sinusoidal waves the critical Reynolds number (Re_{cr}) at which transition starts has been proposed by many researchers as mentioned already. The value generally suggested is around Re_{cr}=1.5x10^5. In the present experiment because of irregularity in the wave shapes, it is expected that apart from being turbulent, some waves essentially would remain in laminar state, thereby, showing properties of all different flow regimes.

In addition to significant wave Reynolds number, Reynolds number corresponding to half wave period and peak velocity (Re_p) has also been utilized in this study.

Table 1: Experimental conditions

Run	$T_{1/3}$ s	ρ g/cm^3	ν cm^2/s	$U_{1/3}$ cm/s	$Re_{1/3}$
Case 1	3.0	0.00122	0.147	242.0	1.9x10^5
Case 2		0.00119	0.152	506.8	8.1x10^5

3. VELOCITY PROFILES

Figure 2 shows recorded raw velocities at selected elevations for Case 2. A wide range of flow situations can readily be identified; turbulent bursting, weakly turbulent and purely laminar conditions. While in the wave terrain waves with relatively higher magnitude show very high turbulent intensities (marked with arrows), the turbulent energy is dissipated in the presence of successive smaller waves.

This energy dissipation process is gradual and needs several smaller waves to fully dissipate the turbulent energy. As a result waves those follow large turbulent waves, show properties of flow turbulence even if the individual waves have Reynolds numbers much smaller, in the range of laminar flow regime from sinusoidal wave consideration (one such location is marked as '*A*' in the figure). On the other hand, several larger waves

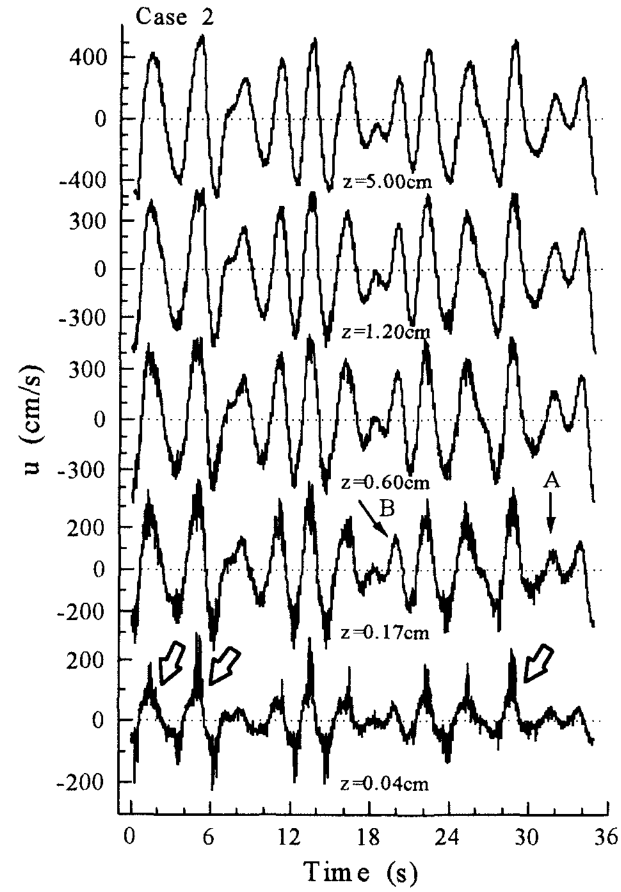

Fig.2: Raw velocity records at selected elevations, Case 2

are required for sufficient build-up of the potential to initiate turbulence generation (marked as '*B*' in the figure). These are characteristic of turbulent motion under irregular waves and would be analyzed in further details.

Figures 3 and 4 show the ensemble averaged velocities at selected elevations along with those from laminar solution. A comparison of input and experimental free stream velocities are also presented in the figures that shows a very good agreement emphasizing the accuracy of experimental system.

For Case 1 (Fig.3) flow over most of the domain shows good agreement with laminar solution. Even at phases where high turbulent energy is present in raw velocity record, ensemble averaged velocity shows only small difference with laminar solution. For Case 1, Reynolds number corresponding to individual half wave period and peak velocity, Re_p, remains in the range of flow transition or in laminar regions for almost the entire wave cycle.

For Case 2 (Fig.4) at phases where high turbulent intensities appeared, close to the wall the ensemble average velocities are much higher in magnitude than

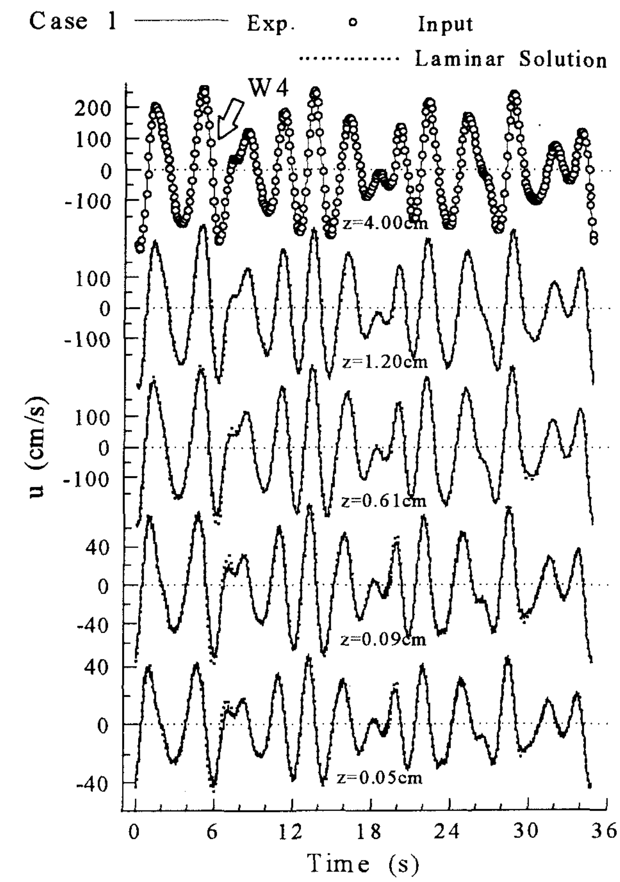

Fig.3: Ensemble averaged velocities at selected elevations, Case 1

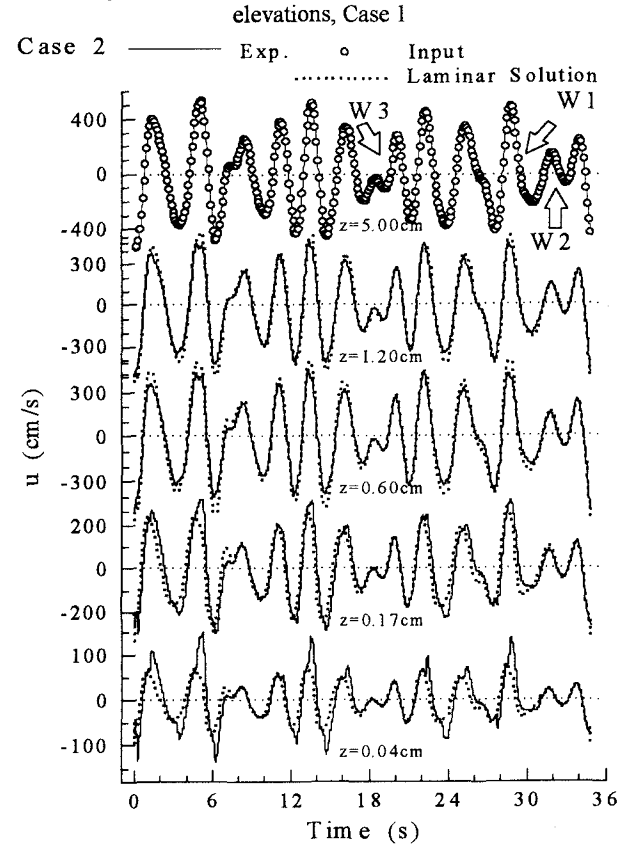

Fig.4: Ensemble averaged velocities, Case 2

corresponding laminar solution, whereas, away from the wall the ensemble averaged velocities reduce suddenly. This phenomena is in agreement with those first pointed out by Hino et al.(1976) under sinusoidal waves. The momentum exchange due to turbulent fluctuations causes velocity acceleration close to the bottom and away from it the flow velocities are reduced compared to corresponding laminar solutions. During transition this can be observed only at phases with high turbulent intensities, that is, in the decelerating phases. Whereas during accelerating phases velocities follow nearly laminar behavior.

The dissipation of turbulence intensities from a larger wave to following smaller waves has been examined in detail in Figs.5 though 8. The high wave at t=28.14s for Case 2 (wave marked as W1 in Fig.4; Re_p corresponding to wave crest and trough are, $Re_{p,crest}$=6.97x10^5 and $Re_{p,trough}$=1.92x10^5) is followed by a much smaller wave with $Re_{p,crest}$ =5.99x10^4 and $Re_{p,trough}$=4.99x10^3 (W2). For the wave W1 the vertical velocity profiles show (Fig.5) a large difference with corresponding laminar profiles due to presence of high turbulent intensities. The Reynolds numbers (Re_p) in the following wave W2 is very small, those represent flow in laminar condition for sinusoidal waves. However, the velocity profiles in Fig.6 still show large differences with laminar solution. Which means that W2 is still affected by the turbulence from W1. Even very small Re_p under wave trough was not enough to completely dissipate the turbulent energy carried into this wave.

Inversely, the initiation of laminar to turbulent transition requires sufficient build up of turbulent energy to produce the first trace of turbulent. Fig.7 shows vertical velocity distribution under wave W3 as marked in Fig.4. W3 has Re_p values as: $Re_{p,crest}$=1.62x10^5 and $Re_{p,trough}$=2.27x10^5. Although these Reynolds numbers are in the transitional range, the velocity profiles show predominantly laminar behavior. Velocity profiles for a different wave (W4 in Fig.3), for which the Re_p are in the same range with W3 ($Re_{p,crest}$=2.17x10^5 and $Re_{p,trough}$=1.62x10^5), are shown in Fig.8 (Case 1). However, the difference with laminar profiles is markedly different between the two with the later showing higher differences at almost all the phases. The reason here also is the carry over of turbulence from the preceding wave. The wave preceding W3 has smaller pressure gradient persistent for a longer period, allowing the turbulence energy to dissipate entirely, as such almost no turbulence has been carried over to W3. On the other hand, in case of wave W4, relatively higher turbulence remained from the preceding wave and, therefore, transitional behavior can be observed.

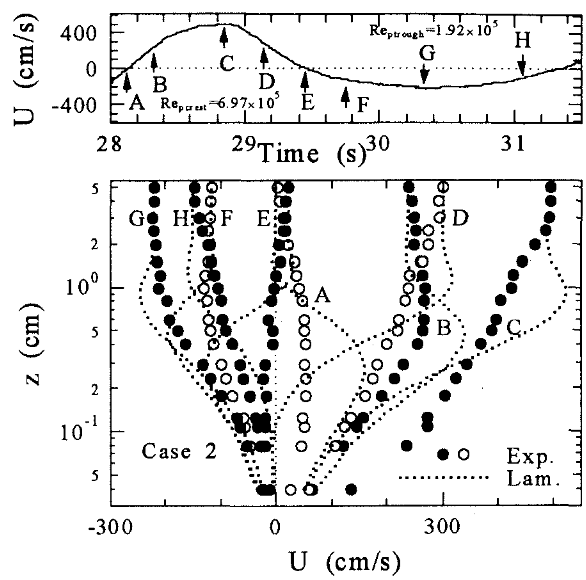

Fig.5: Vertical velocity profiles for wave W1, Case 2

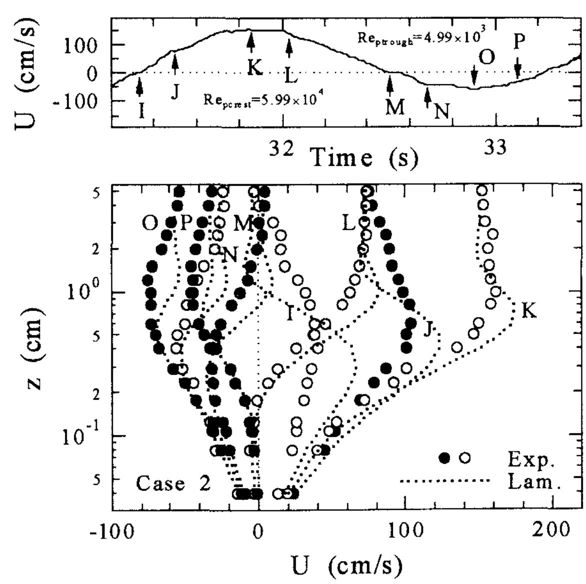

Fig.6: Vertical velocity profiles for wave W2, Case 2

This process of turbulence build-up and dissipation indicates that under irregular waves the state of the flow at an instant is sometime governed by the conditions in the preceding waves. Because of this 'history effect', transitional properties can be observed in waves with relatively smaller Reynolds numbers or the initiation of turbulence may be delayed until a sufficiently larger Reynolds number is achieved. This also poses a difficulty in identifying the flow regime on the basis of conventional sinusoidal wave friction factor diagram alone as would be explained in the later section.

4. TURBULENCE LEVELS AND FLUCTUATING VELOCITY

The phenomena of influence of preceding waves

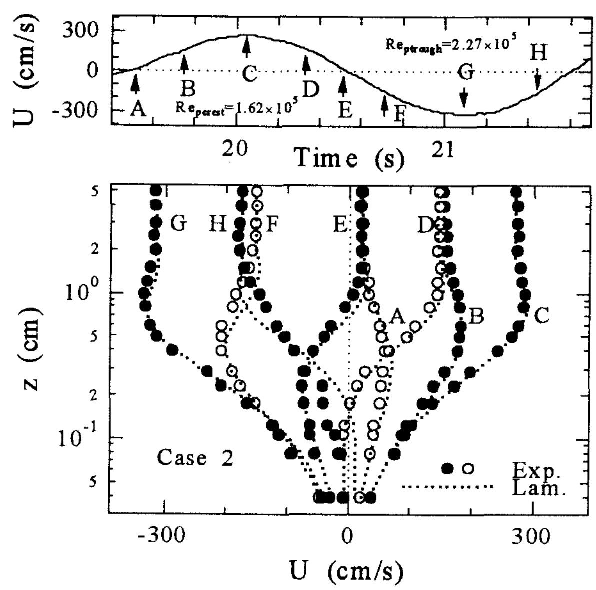

Fig.7: Vertical velocity profiles for wave W3, Case 2

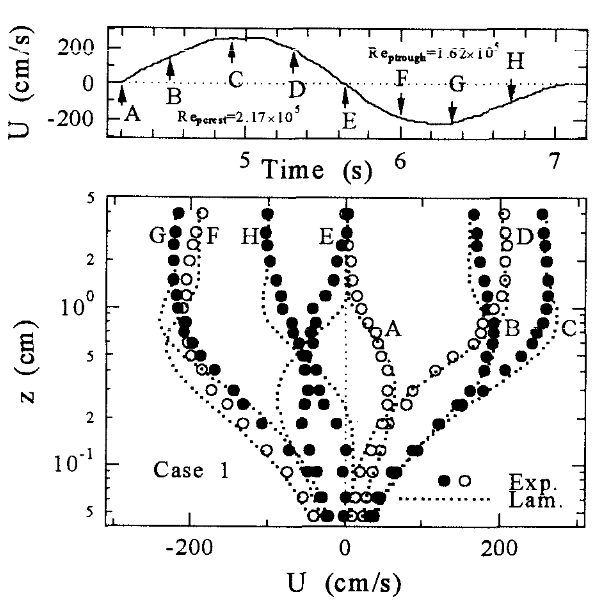

Fig.8: Vertical velocity profiles for wave W4, Case 1

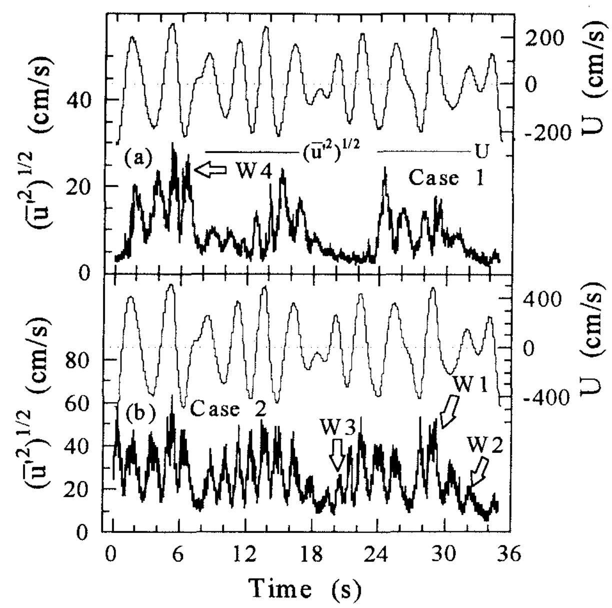

Fig.9: Time variation of vertically integrated kinetic energy; (a) Case 1 and (b) Case 2

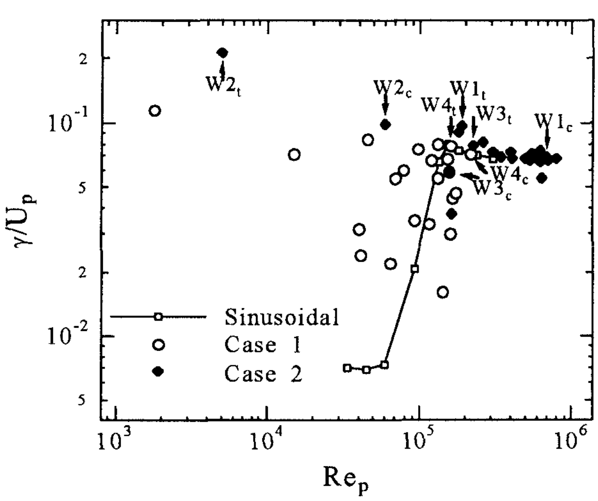

Fig.10: Variation of fluctuating velocities averaged over half wave period with corresponding wave Reynolds number

can further be observed in the time variation of turbulence intensities. Fig.9 shows the time variation of ensemble averaged fluctuating velocities measured at an elevation $z/\delta_l \approx 1.60$ from the bottom along with the variation in free stream velocities, where δ_l is the thickness of Stokes layer $(=(2\nu/\omega_{1/3})^{0.5})$. The magnitude of turbulent intensities for Case 1 is generally very small and shows occasional patches of turbulence. Case 2 shows large turbulent intensities for most part of the wave terrain with one or two segments of predominantly laminar regions. The peaks in turbulent intensities appear under decelerating phases with adverse pressure gradient condition, whereas under accelerating phases favorable pressure gradient forces a decrease in turbulent intensities. Also for pressure gradient remaining small for longer period causes the turbulent energy to dissipate gradually, as a result under sufficiently smaller waves for sufficiently longer period the turbulent energy is completely dissipated as has been explained before.

It can be seen in the figure that for the wave W1 the fluctuating velocity is very large and it gradually dissipates in the following wave W2. Whereas, prior to W3 the turbulent intensities have dissipated with the presence of smaller waves, similar to the behavior observed in vertical velocity profiles.

Time averaging of fluctuating velocities has been done over half wave period and has been defined as $\bar{\gamma}$. For laminar motion this would ideally be zero and would increase with the on-set of turbulence. Fig.10 shows the variation $\bar{\gamma}$ with Re_p along with those for sinusoidal waves. The fluctuations have been measured at the same elevation presented in Fig.9, i.e., at $z/\delta_l \approx 1.60$. Measurements for sinusoidal wave have been performed in order to check the accuracy of the experimental system to reproduce the transitional behavior. Flow transition observed for sinusoidal wave is generally in good agreement with the transitional Reynolds number suggested by various researchers (Jensen et al., 1989; Eckmann and Grotberg, 1991; Verzicco and Vittori, 1996 etc).

At higher Reynolds numbers average turbulent fluctuations is in good agreement with those from sinusoidal waves. However, it shows considerable scatter in the data for transitional range owing to the influence of the so called 'history effect'. As can be seen for wave W2 where very high value of $\bar{\gamma}$ is observed at a much smaller Re_p value.

5. WAVE FRICTION FACTOR

Transition to turbulence in purely oscillatory wave motion is conventionally defined through wave friction factor diagram. Under laminar motion the solution for wave friction factor can be obtained analytically. During flow transition the friction factors deviate from laminar solution and for turbulent motion several empirical relationships have so far been proposed (e.g., Fredsøe and Deigaard, 1992; Samad and Tanaka, 1999 etc).

The influence of flow irregularity on the bottom friction factor under irregular waves has been studied from the friction factors computed for half wave periods in the wave terrain. Fig.11 shows the friction factor diagram corresponding to half wave Reynolds number. From the figure considerable overlap in flow regimes can be observed. While waves with Re_p around $7\text{x}10^5$ have predominantly laminar character, other waves with Re_p around $5\text{x}10^4$ show turbulent properties. As such, the friction factor diagram alone is not sufficient enough to describe the state of transitional flow regime under irregular waves.

6. CONCLUSION

Flow transition under irregular waves has been investigated through laboratory data on bottom boundary layer. Experiments have been performed in a wind tunnel with flow driven by a servo-motor system.

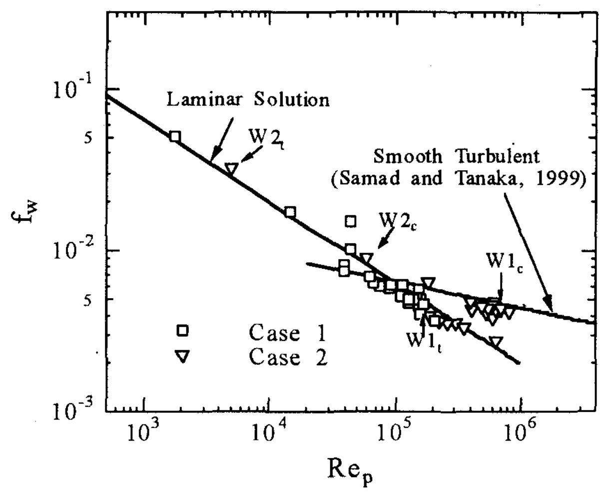

Fig.11: Friction factor diagram corresponding to half wave properties

The processes of turbulence dissipation and build-up indicate that the state of flow under irregular waves is governed not only by the instantaneous flow properties, but also by the conditions in the preceding waves. Because of this 'history effect', transitional properties has been observed in waves with much smaller Reynolds numbers and the initiation of turbulence has been delayed in waves until a sufficiently larger Reynolds number is achieved.

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