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An experimental and numerical study on asymmetric oscillatory boundary layers

Tohoku Univ. member ○ Ahmad SANA
Tohoku Univ. member Hitoshi TANAKA
Tohoku Univ. member Hiroto YAMAJI

1. Introduction: In natural coastal environments, the oscillatory boundary layers are generally asymmetric, i.e. the water surface profile has a sharper crest and flatter trough than the sinusoidal shape. Although there are numerous theories dealing with the asymmetric water surface profile, however, the studies regarding the bottom friction under asymmetric waves are rare, because of the requirement of a sophisticated wave generation system. Recently Tanaka et al.(1996) developed an inexpensive piston movement mechanism by which an asymmetric oscillation, closely approximating the cnoidal wave motion, may be produced in an oscillating tunnel. They validated this system by performing the experiment under laminar condition. In the present study this piston system was utilized to produce higher Reynolds numbers to study the transitional characteristics of asymmetric oscillatory boundary layers.

2. Methodology: The experiments were performed in a U-shaped oscillating tunnel with smooth walls. The velocity was measured by using a one component LDV in forward scatter mode. The data was analysed offline on a PC to get mean and fluctuating components of the velocity. Further detail about the experimental setup may be found in Tanaka et al.(1996). By using air as working fluid, the temporal velocity variation at the axis of symmetry of the tunnel shows excellent agreement with the cnoidal wave theory as shown by Tanaka et al.(1996), however, due to the restricted length of the tunnel, water was used to achieve high Reynolds numbers. But in that case, it was necessary to release the pressure from the tunnel during oscillation because performance of the piston movement system under high pressure was not good. In doing so, a perfect agreement with the theory could not be achieved as may be observed from the velocity at axis of symmetry for the present cases (Fig.1). Table 1 shows the experimental conditions for the cases presented herein. In this table, $A_s = U_c/(U_c + U_t)$, and U_c and U_t are velocity magnitudes at crest and trough, respectively, ν being the kinematic viscosity. The Stokes' layer thicknesses and time periods for crest and trough are given as δ_{lc} $(= \sqrt{2\nu t_c/\pi})$, $\delta_{lt}(= \sqrt{2\nu t_t/\pi})$, t_c and $t_t(= T - t_c$, $T =$ period of oscillation), respectively. The distance between wall and axis of symmetry is denoted by y_h and $\omega = 2\pi/T$.

Table 1. Experimental conditions for the present experiments

Exp.	T(s)	t_c(s)	U_c(cm/s)	A_s	$Re_c = U_c\delta_{lc}/\nu$	$Re_t = U_t\delta_{lt}/\nu$	$RE_c = U_c^2/\omega\nu$	$S = U_c/(\omega y_h)$
N02	2.00	0.84	109.4	0.62	859	616	438000	10.72
N04	3.92	1.66	55.6	0.57	604	541	217000	10.67

The low Reynolds number $k - \epsilon$ model by Jones and Launder(1972) was utilized here for the prediction. For a particular case, the governing equations of this model require only RE_c and S values to provide the solution in dimensionless form. The detail in this regard may be found elsewhere (e.g. see Sana and Tanaka, 1996).

3. Results and comparison: The velocity overshooting at all the phases is stretched in cross-stream direction in comparison with the laminar velocity profiles as per theory described by Tanaka et al.(1996) for Case N02 (Fig.2). The diminished velocity overshooting and the stretching in cross-stream direction may be attributed to high momentum transport resulting from turbulence production. The velocity profile shows a good agreement with the $k - \epsilon$ model prediction just at the beginning of deceleration phase(t/T=0.0), especially where the velocity overshooting occurs. But during the course of deceleration, it seems that the model fails to cope with the flow situations. Considering the boundary layer thickness δ as the distance from the wall to the location of maximum cross-stream velocity at $\omega t = 0$ (or at $\omega t = T/2$) (Jensen, 1989), we have, $\delta \propto \delta_l(= \sqrt{\nu T/\pi})$, consequently the value of δ must be greater under trough than that under the crest due to longer period of time contained in the trough, the experimental evidence of which may be observed from δ values at $t/T = 0$ and 0.5 (Fig.2).

From the contour plots of the x direction fluctuating velocity u' for Case N02 (Fig.3) it may be observed that in a manner similar to that in sinusoidal case, here also the turbulence is produced and distributed in cross-stream direction during deceleration and acceleration phases, respectively. The $k - \epsilon$ model provides the turbulence kinetic energy k, therefore u' has been found by using the approximation; $u' = 1.052\sqrt{k}$ (Nezu, 1977). The qualitative agreement between the model prediction and the experimental data is good in this case.

The wall shear stress for Case N04 was computed by momentum integral method and the wall relationship for viscous sublayer ($\tau_0/\rho = \nu\partial u/\partial y|_{y=0}$). Both these methods yield similar τ_0 profiles here, except at a few phases (Fig.4(a)). The shape of τ_0 profile is similar to that by laminar theory of Tanaka et al.(1996) with higher magnitude showing the beginning of transition. The model prediction shows the secondary peak in deceleration phase contrary to experiment. A good qualitative agreement is found between the shear stress computed from log-fit and momentum integral methods for case N02 (Fig.4(b)). In the deceleration phase during trough period where the logarithmic profile is not clearly observed as may be seen from the velocity profile(Fig.2), the log-fit method yields lower value of the shear stress. The secondary peak in the trough portion is at $t/T \simeq 0.65$. The model overestimates the crest value of τ_0 but trough value shows close agreement with the experiment with different phase difference though.

4. Conclusions: In asymmetric oscillatory boundary layer, the stretching of velocity profile in cross-stream direction at high Reynolds numbers, turbulence generation and distribution properties are similar to those in sinusoidal case, but the boundary layer thickness under trough is greater than that under crest. The low Reynolds number $k-\epsilon$ model by Jones and Launder(1972) showed good performance to predict mean velocity profile during acceleration phase, but during deceleration phase its predictions were not satisfactory. The overall agreement between the model prediction and experimental data is satisfactory for x direction fluctuating velocity. The magnitude of τ_0 was predicted satisfactorily with the discrepancy in phase difference.

References

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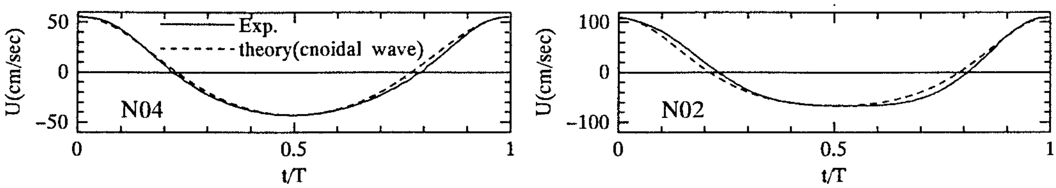

Fig.1 Temporal velocity variation at the axis of symmetry.

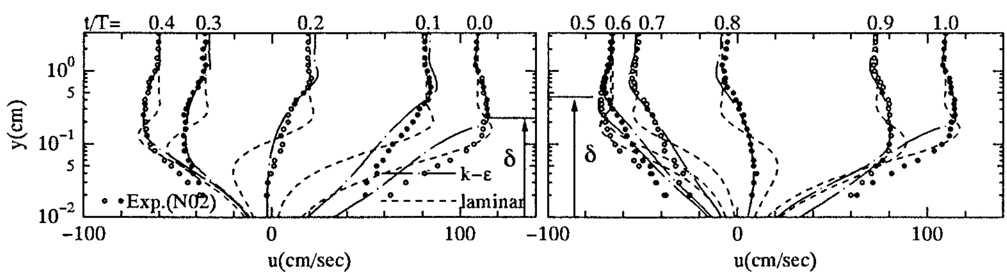

Fig.2 Velocity profile for Case N02 ($U_c = 109.4cm/sec$, $Re_c = 859$, $A_s = 0.62$).

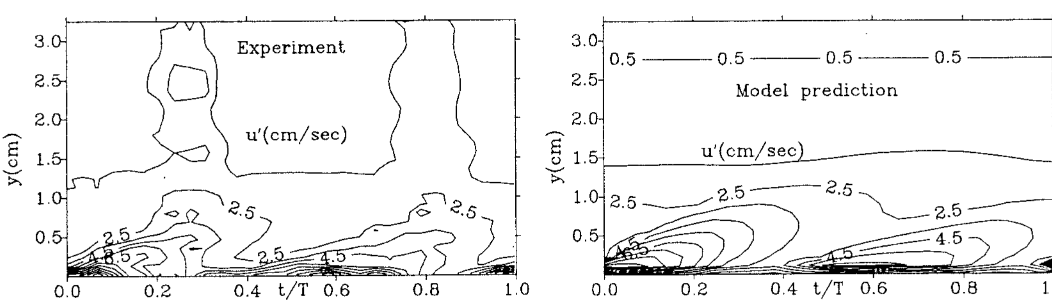

Fig.3 Contour plots of fluctuating velocity in x direction for Case N02.

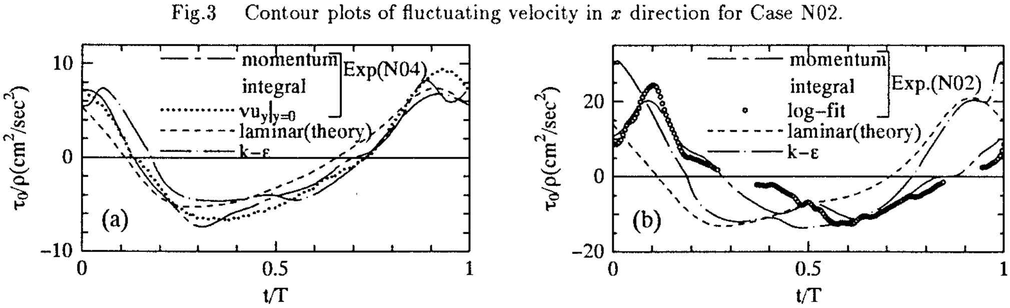

Fig.4 Temporal variation of wall shear stress for (a) Case N04 and (b) Case N02.