The prediction of turbulence intensities in unsteady flow

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Abstract:
This study investigates the distribution of turbulence intensities in unsteady non-uniform flows. Yang & Chow’s (2008) work was extended to express this distribution based on the relationship between Reynolds shear stress and turbulence intensities in unsteady flow. It was found a self-similarity relationship between Reynolds shear stress and turbulence intensities in unsteady flow. This relationship has been developed as empirical equations based on experimental data available in the literature. By applying the self-similarity relationship, good agreements between the measured and predicted turbulence intensities have been achieved.

1. INTRODUCTION

Unsteady flow is a recurrent phenomenon in nature and its turbulence characteristics are difficult to understand due to its dependence of time and space. It is important to understand unsteady flow because its turbulence characteristics are crucial for predicting sediment transport and pollution dispersion in river systems, lakes and coastal waters where the influence of unsteadiness is more significant. The unsteady flow is complicated because in practice it is difficult to predict it due to its variation with time and space and no widely accepted theory has been established and therefore, in this paper, the full profile of turbulence intensities in unsteady flow will be estimated.

Many researchers have studied the distribution of turbulence intensities in uniform flow (Grass, 1971, Laufer, 1974, Eckelmann, 1974, Nakagawa et al., 1975, Dou, 1981, Steffler et al., 1985, Kironoto & Graf, 1994, Nezu & Azuma, 2004 etc.). While Song (1994), Kironoto & Graf (1995) and Song & Chiew (2001) measured turbulence intensities in accelerating and decelerating non-uniform flows and they demonstrated that the distribution of turbulence intensities in non-uniform flow deviates from those in uniform flow. In accelerating flow, this distribution is decreased more than those in uniform flow whereas in decelerating flow their distribution is higher. This deviation has been explained by Yang & Chow (2008) using the Reynolds equation and they concluded that the vertical velocity \(v\) generated from non-uniform flow is responsible for the deviation of turbulence intensities in non-uniform flows from those in uniform flow. They obtained that this vertical velocity can be induced by non-uniform flows. Accelerating flows produce downward velocity whereas decelerating flows generate upward velocity. In order to prove this investigation, Yang & Chow (2008) used experimental data sets from Song (1994) and they found that the measurement of turbulence intensities in decelerating flows is higher than those in uniform flow if \(v > 0\), whereas its measurement in accelerating flow is lower from uniform flow if \(v < 0\). But in practice, the vertical velocity is generally too small to measure. So, they obtained their distribution empirically based on the relationship between Reynolds shear stress and turbulence intensities in non-uniform steady flow.

In unsteady flows, few researchers have studied the distribution of turbulence intensities and none of them restrict their research to flows with a free surface. Over a gravel bed and using an Acoustic Doppler velocity profile (ADVP), Song (1994) measured horizontal and vertical turbulence intensities in an entire water column through negative and positive bed slope. He used uniform equations obtained from Nezu & Rodi (1986) to compare with the measured data sets in unsteady flow. From this comparison, he obtained that the runs with small unsteadiness, there is no difference between the...
normalised turbulence intensities distribution in unsteady and uniform flows; while the runs with large negative bed slope or with high unsteadiness, the horizontal and vertical turbulence intensities distribution are generally different from those of uniform flow.

Nezu et al. (1997) studied the turbulence characteristics in unsteady open channel flow over a smooth bed. They obtained that the values of turbulence intensities may not be affected by the unsteadiness of flow when they compared their measurements with the determined turbulence intensities using the uniform formulas. The reason for this relates to low flow conditions to generate weakly unsteady flow as compared with Song (1994)'s flow conditions.

Based on the review outlined before, turbulence intensities in unsteady flow have little investigations in hydraulic engineering as almost flows in rivers are unsteady or non-uniform flows, and in the literature there is no a universal model to express the distribution of these characteristics in the complex flow conditions, thus more research is needed to predict the distribution of turbulence intensities in unsteady flow. Therefore, the aim of this present study is to extend the work of Yang & Chow (2008) in unsteady flow. The primary objectives for this paper are: (1) Establish a new relationship between Reynolds shear stress and turbulence intensities in unsteady flow; and (2) Verify the developed empirical equations using available experimental data.

2. THE DISTRIBUTION OF TURBULENCE INTENSITIES

In steady non-uniform flow, the empirical estimations of horizontal and vertical turbulence intensities have been developed by Yang & Chow (2008) who introduced a new formula to estimate the horizontal and vertical turbulence intensities depending on the measured Reynolds shear stress. Yang & Chow's formal is proposed based on the mixing length theorem which states that the horizontal $u'$ and vertical $v'$ turbulence intensities are proportional to the product of mixing length. In this study this relationship between turbulence intensities and Reynolds shear stress will be extended to unsteady flow as Song (1994) defined that there is no influence of the unsteadiness on the mixing length. This means that the mixing length distribution in unsteady flow is the same as in steady flow. Therefore, in this study, we follow a similar way that has been used by Yang & Chow (2008) to express new formula for the estimation of horizontal/vertical turbulence intensities in unsteady flow. Song's (1994) experimental data sets in unsteady flow have been plotted in Figure (1a and 1b). In each legend, there are different variables which has been described as Song's definition, for example, $S$ is the bed slope, $NO$ refers to the number of hydrograph in unsteady flow and $(t)$ refers to the time compared with unsteady flow. The measured data sets of horizontal/vertical turbulence intensities and Reynolds shear stress, i.e. $(u', v' \text{ and } -\rho u' v')$, respectively, selected from Song (1994) are presented in the form of normalised turbulence intensities versus the normalised Reynolds shear stress. This normalization is made with respect to the calculation of turbulent intensities and Reynolds shear stress in uniform flow.
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Figure 1: Relationship between horizontal and vertical turbulence intensities and Reynolds shear stress in unsteady non-uniform flow based on selected data sets from Song’s (1994) where solid lines refer to the predicted Equations (1) and (2), S is the bed slope, NO refers to the number of hydrograph in unsteady flow and \( t \) refers to the time.

In Figure (1), the relationship between the turbulence intensities and Reynolds shear stress in unsteady flow has been drawn based on the some profiles selected from Song (1994) and the best fit for these data sets can be approximated by Equations (1) and (2) with most data between the \( \pm 15\% \) error band, which are similar to the relationship has been found in steady flow by Yang & Chow (2008).

\[
\frac{u'_{\text{uns.}}}{u'_{\text{unf.}}} = 0.5 + 0.5 \cdot \frac{-u'v'_{\text{uns.}}}{-u'v'_{\text{unf.}}} \quad (1)
\]

\[
\frac{v'_{\text{uns.}}}{v'_{\text{unf.}}} = 0.4 + 0.6 \cdot \frac{-u'v'_{\text{uns.}}}{-u'v'_{\text{unf.}}} \quad (2)
\]

Equations (1) and (2) describe the relative horizontal \( \left( \frac{u'_{\text{uns.}}}{u'_{\text{unf.}}} \right) \) and vertical \( \left( \frac{v'_{\text{uns.}}}{v'_{\text{unf.}}} \right) \) turbulence intensities in unsteady flow with respect to these turbulences in uniform flow, where the subscript “\text{unf.}” refers to these turbulence intensities in uniform flow and “\text{uns.}” is the predicted turbulence intensities in unsteady flow. These two equations demonstrate the values of these turbulence intensities depending on the relative Reynolds shear stress in unsteady flow with respect to uniform flow, i.e. \(-\frac{u'v'_{\text{uns.}}}{-u'v'_{\text{unf.}}} \). This means that if Reynolds shear stress deviates from the linear distribution, then the distribution of turbulence intensities will be different from that in uniform flows. If the value of Reynolds shear stress in unsteady flow is less than that in uniform flow and then similar observation for turbulence intensities distribution can be expected, vice versa. In order to check the validity of Equations (1) and (2), the remaining datasets from Song’s (1994) experiments except those shown in Figure (1) are plotted in Figure (2), where (UN) refers to unsteady flow, \( S0 \) refers to the bed slope, (NO) refers to the number of each hydrograph and \( t \) is time.
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Figure 2: Comparison of measured and predicted turbulence intensities in unsteady flow based on Song’s (1994) experimental data, where UN refers to unsteady flow, S is the bed slope, NO. the number of hydrograph and t is the time.

Equation 1
Equation 2
u'/u*
v'/u*

(a) UN S-60%, NO.934, t=154 s

(b) UN S-45%, NO.935, t=30 s

(c) UN S-60%, NO.936, t=45 s

(d) UN S-60%, NO.936, t=67 s

(e) UN S-60%, NO.936, t=61 s

(f) UN S-25%, NO.931, t=54 s

(g) UN S-60%, NO.936, t=35 s

(h) UN S-45%, NO.934, t=82 s
Figure (2 from a to h) shows the comparisons of measured and predicted turbulence intensities in unsteady flow based on Song’s (1994) experimental data, where the open circles represent the measured horizontal turbulence intensity $v' / u_*$, the open square are the measured vertical turbulence intensity $w' / u_*$, the solid lines are the calculated values of $u' / u_*$ using Equation (1) and the dashed lines are the predicted $v' / u_*$ using Equation (2). In each diagram, the measured and predicted values are plotted against the relative water depth $y / h$ for different bed slope, hydrograph and times. In order to apply Equations (1) and (2), the full profiles across the water depth for Reynolds shear stress in unsteady flow should be available which is already measured by Song (1994) and therefore, Song’s experimental data is considered to be one of the best available in the literature. While the full profiles of Reynolds shear stress and horizontal/vertical turbulence intensities in uniform flow have been determined based on Yang’s (2009) and Kironoto & Graf’s (1994) equations, respectively, which are selected for rough beds because Song’s data was conducted on a gravel bed with $d_{50} = 12.3$ mm. After knowing the values of $u' / u_*$, $-\bar{u}'\bar{v'}_{uns}$, $u'^2$, $\bar{u}'\bar{v'}_{unf}$, $l u^2$ and $v' / u_*$, where $u_*$ is the shear velocity, the values of $u' / u_*$ and $v' / u_*$ are predicted using Equations (1) and (2), respectively. Based on the above comparison shown in Figure (2), it is clearly seen that the agreement between the measured and predicted values are acceptable.

3. COMPARISON WITH NEZU ET AL.’S (1997) EXPERIMENTAL DATA:

Nezu et al. (1997) measured the full profiles of Reynolds shear stress and horizontal and vertical turbulence intensities in unsteady flow in an open channel 10m long, 0.4m wide and 0.5m deep using a Laser Doppler Anemometer (LDA). They conducted their experiments over a smooth channel. They measured horizontal mean velocity, Reynolds shear stress and horizontal and vertical turbulence intensities using a Laser Doppler Anemometer (LDA). This experimental data will be used to verify Equations (1) and (2). Their measured data of $u' / u_*$ and $v' / u_*$ have been plotted against $y / h$ as open circles and squares, respectively, while the solid and dashed lines are the predicted values of $u' / u_*$ and $v' / u_*$ using Equations (1) and (2), respectively. In each figure, there is a label which refers to the series name (SC3T1) and (t) refers to the rising time (i.e. 36 and 48 s) and the falling time (i.e. 84 and 96 s). Based on Equations (1) and (2), the measured Reynolds shear stress is the main factor to predict other turbulence characteristics, such as $\gamma u'$ and $\gamma v'$. Therefore, the predicted values of these turbulence intensities shown in Figure (3a to 3d) do not appear as smooth lines. Overall, the agreements between the calculated values and experimental measurements are very reasonable.
Figure 3: Comparison of measured and predicted turbulence intensities in unsteady flow based on Nezu et al. (1997) experimental data, SC3T1 is the series name and (t=36s and 48 s) is the rising time while (t=84s and 96s) is the falling time.

4. CONCLUSION

The distributions of horizontal/vertical turbulence intensities in unsteady flow have been investigated. This prediction depends on the ratio of Reynolds shear stress in non-uniform unsteady flow to that in uniform flow, as developed in Equations (1) and (2). A good agreement is obtained when compared the measured turbulence intensities from Song (1994) and Nezu et al. (1997) with the calculated values using Equations (1) and (2).
5. REFERENCES