Experimental and Numerical Study on Turbulent Oscillatory Boundary Layers(水理実験及び数値計算に基づく乱流波動境界層の研究)

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論文内容要旨

Introduction

The understanding of boundary layer characteristics in coastal environments is essential in order to estimate the sediment movement with reasonable accuracy. In natural environments, these boundary layers depict a large variety of characteristics due to the influence of a large number of governing factors like wind speed, bottom slope, sediment size etc. Even the behavior of the most simple wave boundary layers is not completely understood as yet. In order to proceed to more complex oscillatory boundary layers in natural environment, it is necessary to acquire an adequate basic knowledge about the wave boundary layers under sinusoidal and other simple free-stream velocity variations. The present study is aimed at the acquisition of basic knowledge about the oscillatory boundary layers, which are important from practical point of view. To begin with a theoretical situation of the boundary layer under purely sinusoidal motion is considered in order to get acquainted with the basics of various associated processes and quantities. Then the scope is extended to pulsatile motion, i. e. the motion under the combined effect of waves and current, and some intersting features have been found. Although present day coastal engineering field is rich in the wave theories concerning asymmetric waves, however, the details about boundary layer structure under such type of waves are almost untouched as yet. In the present study, cnoidal wave, i. e. one of the asymmetric waves cloesly approximating the actual wave profile, has been produced by using a novel piston oscillation system. The mean and fluctuating components of boundary layer properties under this asymmetric oscillatory motion are collected and studied in detail. In order to establish the theoretical demarcation line between ordinary wave boundary layer and quasi-steady wave boundary layer, the experiments were carried out, probably for the first time using oscillating tunnel.

In order to tackle with the boundary layers under unsteady motion with zero mean (oscillatory motion) or non-zero mean (pulsatile motion) theoretically, there are various options by virtue of the model types, i. e.

semi-empirical, analytical and transport models. Another more expensive and difficult approach is Direct Numerical Simulation (DNS), but it is very far from being practically viable as to the present day. For the case of oscillatory boundary layer, the DNS data for a few cases are available, which were used here to demonstrate the ability of other models.

Semi-empirical methods have been very useful some years ago, but the applicability range of these methods is narrow and depends upon the type of assumptions and the experimental conditions on which these methods are based. The practical viability of analytical models is beyond doubt, however, as the computational resources are becoming accessible and affordable to almost everyone in their powerful form, numerical modeling techniques are gaining popularity. In other words, the simplifications, those were inevitable to get analytical solution, are no longer required. In this study, therefore, transport model was selected to analyze the behavior of boundary layers under consideration.

Naturally, the choice of a certain type of model was difficult to make in the present study, however, considering the conditions of reasonable accuracy along with computational economy and general popularity, the low Reynolds number $k-\varepsilon$ model was chosen. Since the advent of this model by Jones and Launder (1972), a large number of modified models of this kind have been proposed. In the present study, some of the popular and latest versions of this model are employed.

In order to study the mean and fluctuating properties during transition in sinusoidal oscillatory boundary layers from laminar to turbulence, the experiments were performed in an oscillating tunnel with smooth walls.

After getting acquainted with the basic knowledge related to sinusoidal oscillatory boundary layers, the scope was extended to study the boundary layers under asymmetric oscillatory motion. A detailed experimental program was run to explore the boundary layer characteristics related to such type of motion.

One of the interesting phenomenon in real situations is the sediment transport under long waves. But in order to deal with this phenomenon in a precies manner, a comprehensive knowledge about the boundary layer structure under these waves is essential. That is why, the transformation of the oscillatory boundary layer from the ordinary to quasi-steady one was studied by a series of detailed experiments in the oscillating tunnel with rough walls.

Literature review

The present study deals with the oscillatory boundary layers numerically as well as experimentally. Therefore, a comprehensive review has been done keeping both these in mind. It has been endeavored that all the important studies related to the present study may be consulted and referred. There are various state-of-the-art reviews regarding oscillatory boundary layers and turbulence models, those have also been mentioned for the interested readers.

Predictive ability of $k-\varepsilon$ model for oscillatory boundary layers

The use of low Reynold number $k-\varepsilon$ model to analyze the oscillatory layers is not new. But all the previous studies are based on the old versions of this model. As the DNS data became available in the last decade for sufficiently high Reynolds numbers, the $k-\varepsilon$ model was also improved based on these data by many researchers. Some of the most popular modern versions of this model have been tested in the present study against the available experimental and DNS data.

In its generic form, the $k-\varepsilon$ model consists of the equations for transport of turbulence kinetic energy and its dissipation rate, the reason why it is somtimes called two-equation model. These two nonlinear equations along with equation of motion and appropriate boundary conditions are then solved by numerical techniques. In the present case, an implicit finite difference scheme of Crank-Nicolson type was adopted. An exponential grid was generated to achieve better accuracy near the wall. A total of five versions of the low Reynolds number $k-\varepsilon$ model namely by ; Jones and Launder (1972) (JL) , Lam and Bremhorst (1981) (LB) , Myong and Kasagi (1990) (MK) , Nagano and Tagawa (1990) (NT) and Speziale et al. (1992) (SAA) , were employed here.

The experimental data by Jensen (1989) for a turbulent oscillatory boundary layer was used as a test case to compare the predictive ability of the model versions under consideration. In this experiment the velocity was measured by Laser Doppler Velocimeter (LDV) and the wall shear stress was measured by hot film sensor.

The model predictions were tested against this data for mean velocity, turbulence kinetic energy, Reynolds stress and the wall shear stress. A quantitative comparison revealed that although the magnitude of various quantities was predicted in a better way by two of the modern models (MK and NT) , however, these models could not reproduce the transitional properties of the flow. On the other hand, the predictions by the original version (JL) was a little inferior in case of turbulence kinetic energy and the Reynolds stress, but it could reproduce the transitional properties in a better way.

Moreover, the DNS data by Spalart and Baldwin (1989) and Justesen and Spalart (1990) were also utilized to test these models. These data correspond to and of the transitional region between laminar and turbulent oscillatory flow, therefore more demanding by virtue of the complexity of this situation. In this case also, the modern models like MK and NT performed well in predicting the turbulence kinetic energy and showed better agreement near the wall as comared the other models. But JL model was again superior to the rest of the tested models in predicting the transitional behavior.

Prediction of oscillatory boundary layer transition by $k-\varepsilon$ model

The complexity of transition phenomenon from laminar to turbulence in oscillatory boundary layers has attracted many researchers to carry-out experimental investigations in this regard. Here also a series of detailed experiments was performed to observe the changes occurring in the mean and fluctuating velecity, boundary layer thickness, friction factor and phase difference.

An oscillating tunnel was constructed for this purpose by using perspex glass sheets. The vertical risers of the tunnel were connected to two cylinders in which the pistons were made to produce sinusoidal oscillation with the help of an electric motor whose speed may be controlled by a regulator. The velecity measurement was carried out by using one component fiber optic LDV. The oscillating tunnel and the block diagram of velocity measurement system is shown in Fig. 1 .

The experiments were performed to cover the whole range of transition from laminar to turbulence, the guideline for which was obtained from previous famous studies like Hino et al. (1976). The validity of the present experimental system was done by using laminar theory and the available DNS data.

The most interesting results include the stretching of mean velocity profile in cross-stream direction, increase in turbulence intensity, decrease in the phase difference, abrupt increase in the boundary layer thickness and friction factor at critical Reynolds number. The numerical prediction of the transition phenomenon was done by $k-\varepsilon$ (JL) model and a close agreement with the experimental data was found. Especially the mean velocity profile was predicted in an excellent manner and good qualitative agreement was found for turbulence intensity. The prediction for boundary layer thickness, friction factor and phase difference also depicted good agreement with the data.

Performance of $k-\varepsilon$ model to analyze the boundary layer under wave-current combined motion

In many coastal environments, the interaction of waves and current plays a major role in the sediment transport. In order to deal with this problem in an effective manner, accurate knowledge of boundary layer properties is essential. To check whether $k-\varepsilon$ model may provide the required information about flow properties under this type of complex motion with reasonable accuracy, the experiments were performed and the numerical prediction was done.

For the experiment, the experimental setup shown in Fig. 1 was used, where the sinusoidal oscillation was produced by piston mechanism and the steady current was generated by the centrifugal pump installed with the oscillating tunnel. For the numerical prediction, JL, MK and NT model were employed here.

It was observed that three of the models can predict the mean velocity profile in an excellent manner, but a discrepancy was found in predicting the deformation of the current component. The predicted turbulence intensity showed good agreement with the data. Although JL model underestimated the wall shear stress to some extent, MK and NT models showed satisfactory agreement.

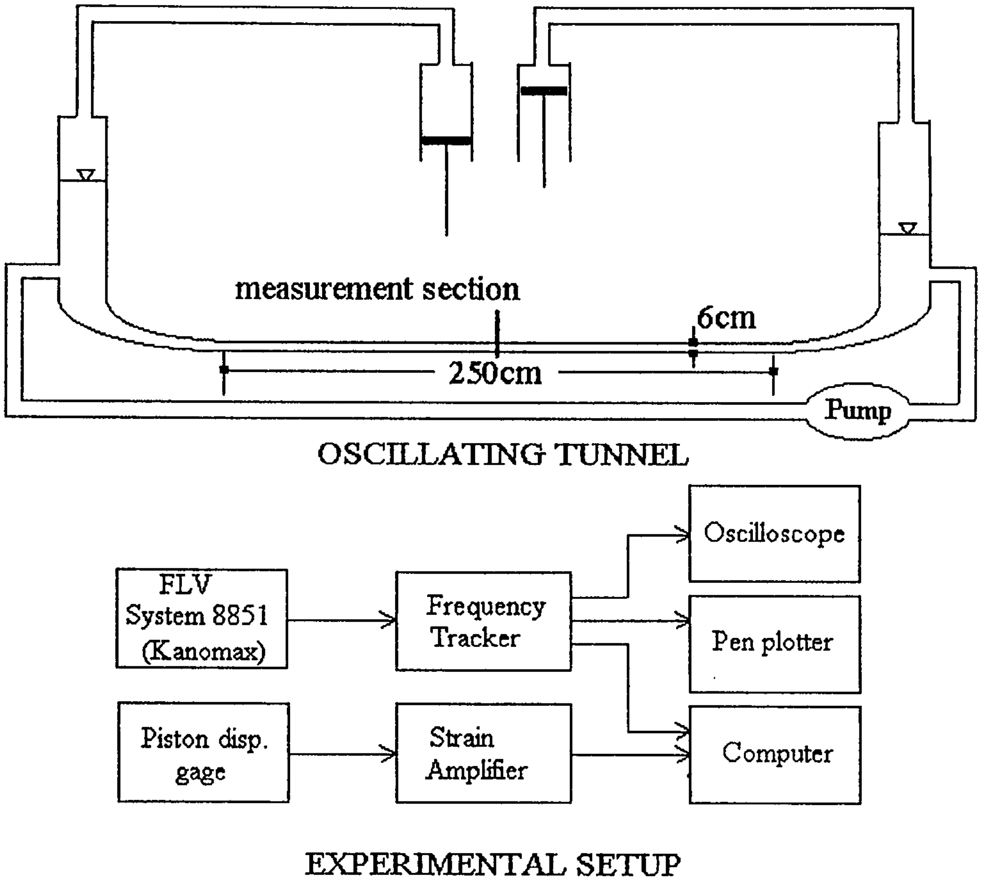

Fig. 1 Oscillating tunnel and velocity measurement system.

Asymmetric oscillatory boundary layers

In the real coastal environments, the oscillatory boundary layers are often asymmetric. Although the wave theories dealing with asymmetric waves are numerous, very little is known about the boundary layer properties under such type of waves. The main reason for the scarcity of the experimental data in this regard is due to highly sophisticated and expensive system to generate asymmetric oasillation. In the present study an inexpensive novel piston mechanism is used to generate asymmetric oscillatory motion closely approximating the cnoidal wave motion.

Another oscillating tunnel was constructed in accordance with the new piston dimensions to produce the oscillatory flow under sufficiently high Reynolds numbers. The configuration of the new oscillating tunnel is similar to that shown in Fig. 1 with a difference in tunnel dimensions. Initially the experiments were performed by using air as the working fluid, but due to the restricted length of the tunnel, very high Reynolds numbers could not be achieved. Therefore, water was used as the working fluid in order to perform the experiments under high Reynolds numbers.

It was observed that the turbulence intensity during the deceleration phase was higher as comared to that at similar Reynolds number in sinusoidal oscillatory boundary layers due to steeper acceleration that in the later case. Even though the Reynolds number during trough phase was smaller than the critical Reynolds number in sinusoidal oscillatory boundary layers, the turbulence intensity was considerable in one of the experimental cases. The numerical prediction was done by the $k-\varepsilon$ (JL) model and it was observed that although during the acceleration phase the model performance was good for mean velocity, however, during deceleration phase the model prediction was not so good. A good qualitative agreement between the model prediction and experimental data was found for turbulence intensity over the whole period of oscillation.

Quasi-steady oscillatory boundary layer on a roungh bottom

In the estimation of sediment movement under long waves, a typical example of which is tsunami, normally Manning's equation is used to calculate the friction factor. In other words it is assumed that the long waves obey steady friction law in whole the range of field conditions. In the present study, a series of experiments was performed to observe the transformation of ordinary wave boundary layers to quasi-steady ones. For this purpose, two-dimensional triangular roughness was applied to the top and bottom of the oscillating tunnel shown in Fig. 1. The roughness height and friction factor were estimated by ysing the method described by Jonsson and Carlsen (1976).

It was observed that with the increase in $\hat{u}_0/\omega y_h$ ($\hat{u}_0$ =amplitude of cross-stream average velocity, $\omega=2\pi/T$ angular frequency, T=period of oscillation, y_h=distance from the theoretical wall to axis of symmetry of the tunnel), the boundary layer changes from ordinary to quasi-steady oscillatory boundary layer. This fact is in accordance with the theory of Tanaka and Shuto (1994) based on one layer analytical model. They proposed a criterion for the demarcation between the two types of oscillatory boundary layers, the validity of which was checked here as well. Another modified criterion was proposed based on the present experimental data. Finally a practical example has been presented to elucidate the usefulness of the present study on quasi-steady property of oscillatory boundary layers.

審 査 結 果 の 要 旨

海浜での土砂移動現象を論ずるためには，海底面での振動流境界層内の乱流構造を十分に理解する必要がある。本論文では，正弦振動流，一方向流を伴う正弦振動流，非対称振動流，及び長周期波動下境界層について，実験によりその乱流構造を調べるとともに，これらの場に対する低レイノルズ数$k-\varepsilon$モデルの適用限界を明らかにしたものであり，全8章よりなる。

第1章は序論であり，研究の背景を述べている。

第2章では，既往の研究について述べ，本研究の位置づけを明らかにしている。

第3章では，乱流正弦振動流を対象として，実験データ及びDNSデータとの比較をもとに，5つの低レイノルズ数$k-\varepsilon$モデルの優劣を論じた。その結果，砂移動現象と密接な関係を持つ底面せん断応力については，Jones&Launder (1972) のモデルがもっとも高い予測精度を有し，一周期内の再層流化現象までも適切に予測できることが判明した。これは工学上重要な知見である。

第4章では，低レイノルズ数$k-\varepsilon$モデルによる振動流の乱流遷移現象の予測精度を検討するために，U字管振動流装置により得られた知見との比較を行った。その結果，第3章で得られた結論と同じく，Jonesらのモデルにより流速分布のみならず境界層内の位相の進み，境界層厚さ，摩擦係数などについても遷移特性を良好に再現できることが判明した。これは工学上有用な示唆である。

第5章では，より現実的な砕波帯内での流体現象を理解するために，正弦振動流に一方向流を重ねた実験を行い，重畳による乱流構造の変化，定常流速分布の変形を明らかにした。また，$k-\varepsilon$乱流モデルによるこれらの特性の予測精度についても検討が行われ，有効な知見が得られている。

第6章では，浅海域での非線形波動の特徴である非対称性を有する振動流について検討を行い，乱れ強度，せん断応力や乱流エネルギー収支などの乱流特性について，正弦振動流場とは大きく異なる性質を明らかにした。この結果は，今後非線形波動による浅海での土砂移動現象を考える際にきわめて重要な知見である。また，非対称振動流発生装置として，従来用いられてきた高価で複雑なシステムに代わる簡便かつ精度の良い装置を試作し，その有効性を確認した。このことは，今後の実験的研究に大きな示唆を与えるものである。

第7章では，津波などの様な長周期性波動の下での振動流境界層について実験的検討を行っている。非定常性が無視できない通常の波動境界層から，各位相での速度分布が定常流に類似しているいわゆる「準定常境界層」に遷移する過程について広範な実験を行い，位相差，摩擦係数，乱れ強度，さらには運動量バランスの変化を調べた。その結果，波動抵抗則と定常流抵抗則を使い分けるための実用的な判定基準が得られた。これは，今後，津波などの長周期性波動下における砂移動現象を扱う際に利用することが出来，きわめて有用な知見である。

第8章は本研究の結論及び今後の課題を示したものである。

以上要するに本論文は，正弦振動流，一方向流を伴う正弦振動流，非対称振動流，及び長周期波動下境界層について，実験によりその乱流構造を調べるとともに，これらの場に対する$k-\varepsilon$モデルの適用限界を明らかにしたものであり，土木工学，海岸工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。