Application of Thermal Shear Stress Gauge in Study on Shear Stress Measurement on Underwater Bed Surface

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Abstract

Although bed shear stress is one of the important ways to research the basic theory of sediment movement under the action of complex hydrodynamic force, the effective method for measurement of bed shear stress hasn’t formed yet. By application of the new micro-nanotechnology-based thermal shear stress gauge, this paper experimentally researches the bed shear stress measurement in wave flume. The research shows that the thermal shear stress gauge is with high response frequency and good stability and, the measurement results present the basic laws of variation of bed shear stresses under wave action and confirm the feasibility of measuring bed shear stress with thermal shear stress gauge on condition of complex hydrodynamic force.

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1. Foreword

1.1. Research background

Shear stress measurement on underwater bed surface is always one of the key and difficult problems in the hydrodynamic research area. Because bed shear stress is directly related to sediment transport, bed shear stress is the important way to study basic theory of sediment movement, especially under complicate hydrodynamic actions such as wave, wave and current, breaking wave, unsteady flow and so on. If engineers want to do good forecasting of bed erosion and siltation caused by silt transport in project construction, it is necessary to understand sediment transport mechanics clearly. The shear stress measurement on underwater bed surface has the following difficulties: the small amount, quick-changing frequency and tough environment, the effective method for measurement of bed shear stress in wave or complex hydrodynamic force hasn’t formed yet. To some extent, it restricts theoretical research of sediment transport. So it is of considerably practical and theoretical sense to research on bed shear stress measurement in complex hydrodynamic force.

1.2. Research advances

At present, it mainly has two methods called direct measurement and indirect measurement to measure bed shear stress. Direct measurement is to calculate the shear stress by measuring displacement of the stress plate (Qin Chongren 1999, Huo Guang 2007, Mirfenderesk and Young 2003). Indirect measurement is to calculate the shear stress by theoretical formula after measuring the fluctuation velocity in the boundary layer on the bottom of water body (Sleath 1988). Because the fluctuation velocity measurement in the boundary layer is very difficult and less accurate, the indirect measurement is infrequently applied in the actual research. When directly measuring bed shear stress by stress plate, it exists the following problem that the pressure change caused by wave surface has effect on the measuring accuracy of shear stress under. Thus it can be seen that it is lack of some effective method to measure bed shear stress underwater under wave action. In the 1980s, researchers begun to study and use thermosensitive shear stress gauge based on the micro-nanotechnology to measure wall shear stress in the airflow, and to some extent promoted the development of aerodynamics (Haritonidis J.H. et al. 1989, Jonathan W. N. et al. 2002). With the development of the Micro Electro Mechanical System (MEMS), micro thermosensitive shear stress gauge has been gradually applied to measure shear stress underwater and achieved some research achievements (Xu Yong et al. 2005, Liang Ting et al. 2010). However it still needs to do more profound research work to apply micro thermosensitive shear stress gauge under complex hydrodynamic force.

2. Testing method

2.1. Operating principle of thermosensitive shear stress gauge

This test used the thermosensitive shear stress gauge based on the micro-nanotechnology to measure bed shear stress. The operating principle of micro thermosensitive shear stress gauge is that when passing the thermosensitive gauge surface, the water takes away heat quantity, and then the output voltage of thermosensitive gauge will change correspondly. It has two operating modes called the constant current mode and the constant temperature method. The constant current operating mode is now applied in this test. In the constant current operating mode, the electric current passing the sensor remains constant.

The thickness of gauge is about 50 micrometers and its maximum output frequency can reach over 100 HZ. The gauge was stucked to the bed surface in the flume test, shown in Fig.1. Compared with the shear stress plate measuring method, the thermosensitive stress gauge has some advantages, such as high response frequency, no pressure influence by wave surface and convenient operation. In the constant current operating mode, the heat balance equation (Xu Yong, 2002) is writen as following:

\[ U = A + Br^n \]  

(1)
Where: $\tau$ is the shear stress(unit: pa), $U$ is the output voltage of thermosensitive sensor(unit: v); the constant parameter $A$, $B$ and $n$ can be obtained by the calibration tests.

![Wave direction]

**Fig.1. The micro thermosensitive shear stress gauge in the test**

### 2.2. Calibration tests

The standard shear stress value can be obtained by the flat and thin rectangular channel(Schetz J.A. et al. 1996). The principle of calibration test is to build a flat and thin rectangular channel with two parallel plates, in order to form the laminar current in the tiny space. In this calibration test, the flat and thin rectangular channel’s width is 10 mm and height is 0.63 mm. We can obtain different standard shear stress value by adjusting the discharge of the rectangular channel. The water temperature is 11.6 °C in this calibration test. The calibration result is shown in Fig.2. The individual value of parameter $A$, $B$ and $n$ is 7.8450, 0.0875 and -0.2950 by data fitting in the standard equation(1), with the fitting correlation coefficient of 0.85. The shear stress calibration equation in the water temperature of 11.6 °C, can be written by the equation (2) (Xu Hua et al. 2013).

$$U = 0.0875\tau^{-0.2950} + 7.8450$$  \hspace{1cm} (2)

![Fig.2 Calibration curve of the thermosensitive shear stress gauge]

### 2.3. Test flume and conditions

The measurement test of shear stress underwater bed surface is done in a long and straight water flume with the length of 175m, the width of 1.2m and the height of 1.6m. The bed of the test flume is smooth cement plaster. The sketch of test layout is shown in Fig.3. The wave height gauge has a measurement accuracy of 0.1mm. In the shear stress measurement tests, water depth of test is 0.20 to 0.65m, and regular wave height of test is 0.05 to 0.30m, and regular wave period of test is 1.2~2.5s, and water temperature is about 11.6 °C(Xu Hua et al. 2013).
3. Analysis on testing results under wave action

3.1. Response frequency and stability of shear stress gauge

The variation process of output voltage measured by the thermosensitive shear stress gauge is shown in Fig.4. The output frequency is 100 HZ. As shown in the figure, there are individually two wave crests and troughs in a period of the voltage variation process. The point in the crest of voltage process shows the minimum value of bed shear stress, and the point in the trough of voltage process shows the maximum value of bed shear stress. The output voltage results show that the thermal shear stress gauge is with high response frequency and good stability.

3.2. The variation rule of bed shear stress

When the water depth $h=0.54m$, the wave height $H=0.24m$, and the wave period $T=2s$, the corresponding relationship between theoretical shear stress and the measured voltage process of the thermal shear stress gauge in one period is indicated in Fig.5. The theoretical shear stress can be calculated by Jonsson’s theoretical formula (3) in wave action. The coefficient of bed friction resistance is associated with the condition of bottom boundary layer...
flow. When Reynolds number exceeds 12,600, the bottom boundary layer will in a state of turbulent current. The formulas of the coefficient of bed friction resistance for different flow conditions of the bottom boundary layer are as below:

\[ \tau_w = \frac{1}{2} \rho f_w u_w^2 \]  

(3)

In the state of laminar condition,

\[ f_w = \frac{2}{\sqrt{Re}} \]  

(4)

In the state of smooth turbulent condition,

\[ f_w = 0.184 Re^{-0.265} \]  

(5)

In the state of rough turbulent condition,

\[ f_w = 0.001 \exp\left[5.96 \left(\frac{A_m}{K_s}\right) - 0.155\right] \]  

(6)

Where, \( f_w \) stands for the coefficient of bed friction resistance in wave action, \( u_w \) for the velocity of the bottom particle, Reynolds number \( Re = \frac{u_w A_m}{v} \), in which \( A_m \) is the maximum moving amplitude of bottom particle, and \( K_s \) is the bed roughness.

In the tests, the bottom boundary layer is in a state of smooth turbulent condition. As shown in the Fig.5, in the voltage variation process there are two low troughs which are respectively correspond to the highest moment of the positive and negative velocity. As the positive velocity is faster than the negative, the output voltage of positive velocity is smaller than that of the negative. The variation principle of output voltage process measured by the thermosensitive shear stress gauge is generally in correspondence with that of theoretical shear stress and hydrodynamic process.

3.3. Comparison between measurement and calculation of shear stress

When the water depth \( h=0.54m \), the wave height \( H=0.22m \), and the wave period \( T=2s \), the process of measured shear stress and theoretical shear stress variation are shown as Fig.6 in one period. As shown in the Fig.6, the variation rule of measured shear stress process is generally in consistency with that of theoretical shear stress process and the results of the thermal shear stress gauge show the basic change rules of bed shear stress in wave action. The relationship between of measured shear stress by the thermal shear stress gauge and theoretical shear stress is shown in Fig.7, in which the deviation between the measured shear stress values and theoretical calculated...
values of 85% scattered points is within 20%. Based on the above analysis, it can be concluded it is generally feasible to use thermal shear stress gauge to measure bed shear stress in wave action.

**Fig. 6** Comparison between measurement and calculation of shear stress in one period

4. Conclusion

This paper using the thermal shear stress gauge based on micro-nanotechnology measured and researched the response and variation rules of bed shear stress through the wave flume tests. The research shows that the thermal shear stress gauge is with high response frequency and good stability, and the measurement results reflect the basic rules of variation of bed shear stress under wave action. In general, the measurement result of the thermal shear stress gauge is reasonably credible, and it is generally feasible for measuring shear stress on condition of complex hydrodynamic force. The measurement accuracy of the new gauge needs to be done further study in the future.

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References

Qin Chongren, Qiu Xueyan, Li Dejun, Chao Chongjiu, 1999. A Study of Bottom Shear Stress of Laminar Boundary Layer in Random Waves. Journal of Hydraulic Engineering, 12: 48-52.

Huo Guang, 2007. A Study of Sediment Movement on Wave Flow Boundary Layer. Nanjing, Hohai University, 1-51.

Hamid Mirfenderesk, Ian R. Young, 2003. Direct measurements of the bottom friction factor beneath surface gravity waves. Applied Ocean Research, 25: 269-287.

Sleath JFA, 1988. Transition in oscillatory flow over rough beds. Journal of Waterway, Port, Coastal Ocean Engineering, 114: 18-33.

Haritonidis J.H, 1989. The measurement of wall shear-stress. In: Gad-el-Hak M, editor. Advances in fluid mechanics. Berlin: Springer, 229-261.

Jonathan W. Naughton, Mark Sheplak, 2002. Modern developments in shear stress measurement. Progress in Aerospace Sciences, 38: 515-570.

Xu Yong, Lin Qiao, Lin Guoyu, et al., 2005 Micromachined Thermal Shear-Stress Sensor for Underwater Applications. Journal of Microelectromechanical Systems, 14(5): 1023-1030.

Liang Ting, Xia Yunfeng, Xu Hua, Ma Binghe. 2010. A Primary Study of Bed Shear Stress Wave Measurement in Waves and Flows. Journal of Waterway and Harbor, 31(5): 425-428.

Xu Yong, 2002. Flexible MEMS Skin Technology for Distributed Fluidic Sensing. USA: California Institute of Technology Pasadena, 1-136.

Schet J.A., Fuhs A.E., 1996. Handbook of Fluid Dynamics and Fluid Machinery. Vol. 1: John Wiley & Sons, Inc, 1921-1989.

Xu Hua, Xia Yunfeng, 2013. A Study of Bed Shear Stress Experiment in Both Waves and Flows. Nanjing Hydraulic Research Institute, 1-70.