Effect of Wall Roughness on Velocity Distribution in Channel Flow (Relation between the Vortex Pattern in Roughness Groove and Flow Pattern over the Rough Wall)

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Abstract

The present paper was concerned with a part of series of the numerical study on the flow in a two-dimensional rough wall channel by authors. On the flow through a two-dimensional channel with repeated squre ribs, the Navier-Stokes equations were solved by the finite difference method. The several flow cases for the pitch ratio $W/h=2\sim 11$ (W and h denote the roughness spacing and height, respectively) and the Reynolds number $Re=5\sim 3000$ were calculated. In order to reserach the effect of wall roughness on the flow pattern over the rough wall surface, the velocity distributions were presented in this paper. As the results, the velocity distribution near the wall showed the periodic flow pattern in the similitude of roughness geometry, and its flow pattern became indistinct with increasing the distance from the wall surface. The distance from the wall surface to the location of indistinct periodic flow pattern depended on both the pitch ratio and the Reynolds number. It was noticeable results that the vortex pattern in the roughness groove was closely related with this distance of indistinct periodic flow pattern.

1. Introduction

The flow structure over the rough wall, the analysis of which is an important problem for the fluid mechanics and heat-transfer [1,2], depends on many parameters such as the roughness shape, height, spacing, and others. The pitch ratio of spacing to roughness height is a dominant factor on its flow structure [3,4], so that the detailed measurement has been made over the extremely wide range from the low pitch ratio (quasi-smooth flow) to the high pitch ratio (semi-smooth flow) in the turbulent flow [5]. In recent years, the importance of the analysis for the flow over the rough wall in the condition of relatively low velocity region has been increasingly recognized; the cooling flow over the circuit bord mounted IC packages [6], the flow through a medical devices such as a membrance oxygenetor and a kidney dialyzer for the purpose of enhancing the mass transfer rates [7], the blood flow in artery or arterial

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prostheses (in medical applications, turbulent flow must be avoided because of the risk of damage to form elements in blood, so the laminar flow is rather to be used) [8] , and so on. In spite of the demand from various engineering fields as described above, it can not be declared that the fundamental data sufficiently obtained for the laminar flow over the rough wall. In a recent papers by authors [9~15] , the laminar flow through a two-dimensional rough wall channel, where the rough wall consists of the repeated squre ribs, has been investigated numerically. In the extensive region of pitch ratio and Reynolds number, the detailed calculation have been performed for the cases of both parameter to be changed systematically [9,10] . In those reports, remarkable results for the flow pattern near rough wall surface were presented as follows; the flow over the rough wall showed the periodic flow pattern in the similitude of roughness geometory. On the other hand, the stable separation vortex was observed in the roughness groove and its vortex shape varied with both pitch ratio and Reynolds number. The variation of its vortex pattern was classified into three cases, and was expressed as the division chart in W/h-Re plane [9] .

The effect of wall roughness on flow structure is very important on a purely fluid mechanical point of view. In addition, a knowlege of flow structure near the rough wall (or in the roughness groove) is also interesting for understanding heat-mass transfer whether they are obtained experimentally or computationally. However, it is difficult to measure the flow properties in a roughness groove, so the numerical results has a very important significance in the prediction of flow structure in the roughness groove. Moreover, if we know the relation between the flow pattern over the rough wall and the vortex pattern in the roughness groove, the flow structure in the roughness groove can be immediately predicted from only measurement flow data over the rough wall. In this report, on the ground of mentioned above, the velocity distributions near the rough wall to be affected by the roughness elements are presented, and are discussed for the relation between the periodic flow pattern over the rough wall and the vortex pattern in roughness groove.

2. Basic Equation and Calculation Model

Consider the laminar flow in a two-dimensional channel with roughness elements. The governing equations for a two-dimensional flow are the Navier-Stokes equations and the continuity equation. By introducing the vorticity ω and the stream function ψ, one obtain the vorticity transport equation in the well-known form

$$\frac{\partial\omega}{\partial t}=\frac{\partial\psi}{\partial x}\frac{\partial\omega}{\partial y}-\frac{\partial\psi}{\partial y}\frac{\partial\omega}{\partial x}+\frac{1}{Re}\nabla^2\omega, \tag{1}$$

$$\omega=-\nabla^2\psi, \tag{2}$$

here, $\nabla^2=\partial^2/\partial x^2+\partial^2/\partial y^2$,

where Re is the Reynolds number, $Re=UH/v$, U denotes the mean fluid velocity in the channel, H the width of channel and v the kinematic viscosity of the fluid, respectively. Equations (1) and (2) are expressed in the non-dimentional forms using the reference length, velocity and time being H, U and H/U, respectively.

The calculation model is the same as given in the previous paper [9,10] , hence, only outline on the model is described as follow; the roughness elements are of the repeated squre ribs ($a=b$) type with spacing W and roughness height h ($h/H=0.1$). Assuming that the flow is periodic corresponding to the roughness periodicity and symmetric with respect to the center line, so the computational region can be considered only lower half of the finite region where the length along the channel is equivalent to the roughness spacing W (Fig. 1). In this computational region, the boundary conditions are givin as (i) the velocity vanishes on the wall surface by the condition of non-slip and of non-penetration at the wall, (ii) $\psi in=\psi out$ and $\omega in=\omega out$ on the in-flow and out-flow boundaries by the periodic flow condition, (iii) $\psi=0.5$ and $\omega=0$ on the center line by the condition of symmetrical flow with respect to the center line.

The difference equation are derived from the equations (1) and (2), and are solved by the pseudo-unsteady method in order to obtain the steady solution as $t\rightarrow\infty$. The mesh constant and time step are taken to be $\triangle x=\triangle y=1/100$ and $\triangle t=0.001\sim0.005$, respectively. The convergence criterion is defined as $|\psi^{(n+1)}-\psi^{(n)}|\leqq10^{-5}$(superscript (n) indicates the valule at the n-th loop) and $|\omega(t+\triangle t)-\omega(t)|\leqq10^{-5}$. Calculated flow cases are also the same as the previous papers [9,10] (see Table. 1).

3. Results and Discussions

3.1. *Flow pattern over the rough wall*

The flow over the rough wall shows the periodic flow pattern (refer to the previous paper [9] for detailed). In Fig.2, the streamwise velocity distribution, $u(x)$, for the constant height from the top of rib is shown for $W/h=7$ and $Re=5$ as the typical case. The periodic distribution is observed in the similitude of roughness geometry. As can be seen in Fig.2, the velocity near the wall increases just above the roughness groove, otherwise decreases at the portion over the rib. On the other hand, that of central region shows contrary results. In order to express clearly as described above, the distribution of fluctuating velocity component, $\tilde{u}(X)$, from mean velocity $\tilde{u}$ (averaged a roughness spacing W) at the constant height is shown in Fig.3. The region in the

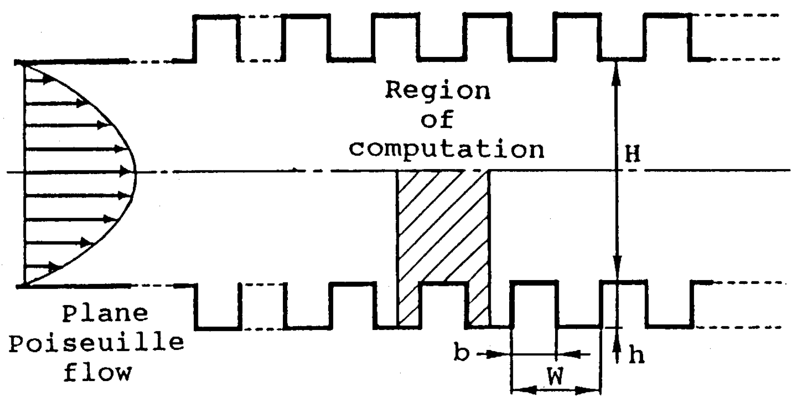

Fig.1 Calculation model

Table. 1 Calculated ranges of pitch ratio and Reynolds number

symbol	Pitch Ratio (W/h)	Reynolds Number (Re)			
		$\times 10^0$	$\times 10$	$\times 10^2$	$\times 10^3$
▼	1.8			1, 1.2	1, 1.2
●	2		1, 1.2	1.5, 2	
▽	2.2			2.5, 3	
◪	2.4		1.5, 2	4, 5	1.5, 1.7
◩	2.8			6, 7	
○	3		2.5, 3	8, 9	
⬢	3.4	5, 9		1, 2.5, 5.7	2, 2.5
⬡	3.6		4, 5	1, 1.2, 1.5, 2.5, 5.7	
▲	4			1, 1.2	
△	5		6.7	1.5, 2	3
■	6			2.5, 3	
□	7		8, 9	4, 5	
◆	9			6, 7	
				8, 9	
◇	11	5	1,2.5,5,7	1, 2.5, 5.7	1, 1.2, 3

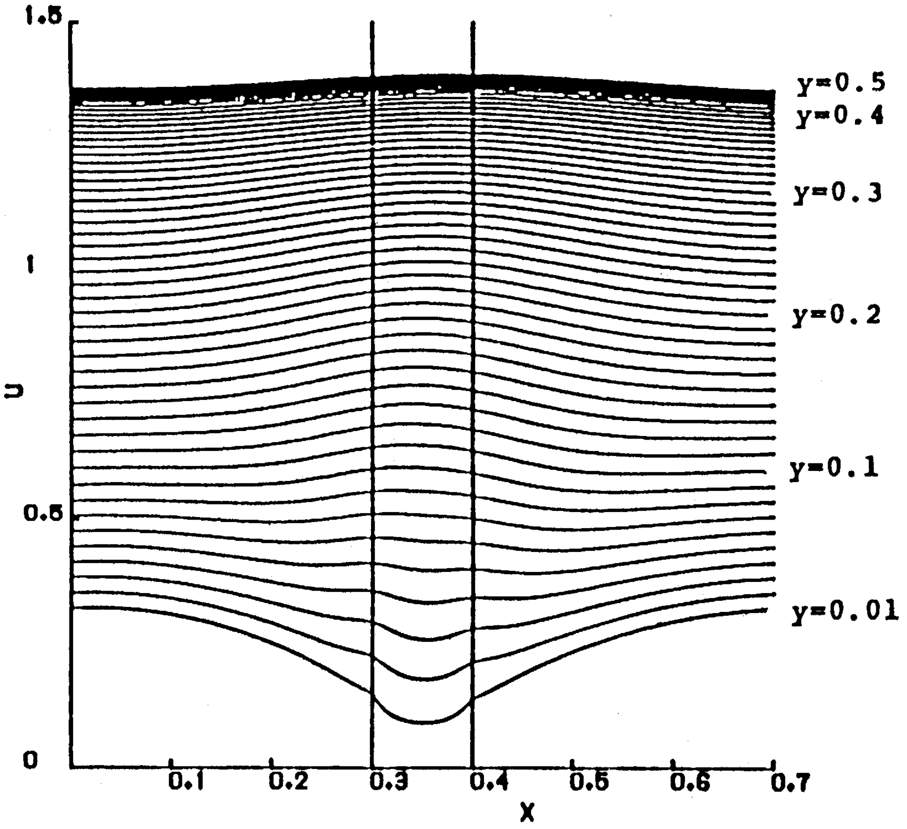

Fig. 2 Velocity distribution at the constant height ($W/h=7$ and $Re=5$), Flow is left to right.

tendency of increasing velocity above the groove and decreasing velocity over the rib is $0 < y < 0.05$, and that of contrary result is $0.05 < y$ (see Fig. 3(a) and (b)). It is noteworthy result that the form of periodic velocity distribution $\tilde{u}$ in the limited region of $0.04 < y < 0.07$ shows higher-mode compared with that of central region (which shows almost sinusoidal form). As the governing equations, that is, Navier-Stokes equations are non-linear partial differential equation, it is quite natural that higher-models appear in the calculated results. The periodic flow over the repeated roughness elements is not peculiar phenomena for the laminar flow, for instance, the periodic velocity distribution at the center line was reported for the turbulent flow in rough wall

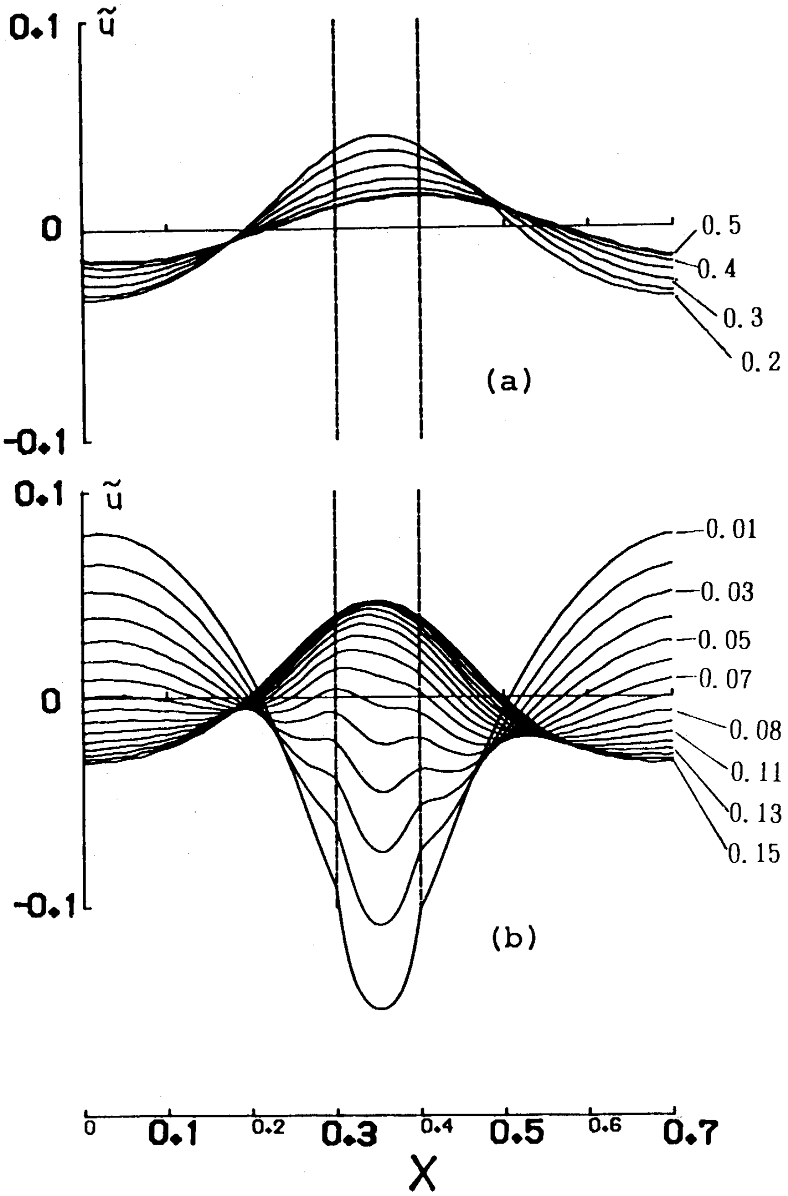

Fig. 3 Distribution of the fluctuating velocity component $\tilde{u}$ at the constant height (W/h= 7 and Re=5), Flow is left to right. (a) y=0.2~0.5, (b) y=0.01~0.2

pipe by Stukel et al. [16] . In addition, the measurement velocity distribution in the turbulent boundary layer over the rough flat plate, reported by Osaka et al. [17] , was also observed the periodic velocity distribution and the existence of its higher-mode form near the wall. For the same flow case ($W/h=7$, $Re=5$), the distribution of normal velocity component v at the constant height is shown in Fig. 4. The distribution of v is also periodic flow pattern, however, higher-mode form resulting from non-linear effects does not appear clearly compared with that of u.

3.2. *The effect of W/h and Re on periodic flow pattern*

The amplitude of periodic flow $\triangle u$, where $\triangle u$ is determined from the maximum difference between $u(x)$ and $\tilde{u}$ at the constant height, is plotted against y for the cases of $W/h=2\sim7$ and $Re=5$, 1000 as shown in Fig.5. It is evident in this figure that the value of $\triangle u$ decreases as the pitch ratio decreases. From comparing the curves between $Re=5$ and $Re=1000$ with the same value of W/h, $\triangle u$ decreases as the Reynolds number increases. $\triangle u(y)$ for $Re=5$ shows the profile with maximum and minimum points. For the case of $Re=1000$, the profile of $\triangle u(y)$ without the minimum point is observed, and the value of $\triangle u$ decreases almost exponentially with increasing distance from wall. Fig 6. shows the profile of $v(y)$ at $x=0.02$ and 0.18 for $W/h=2$, and at $x=0.11$, 0.3 and 0.49 for $W/h=6$ (where, $x=0$ is the position at the center of

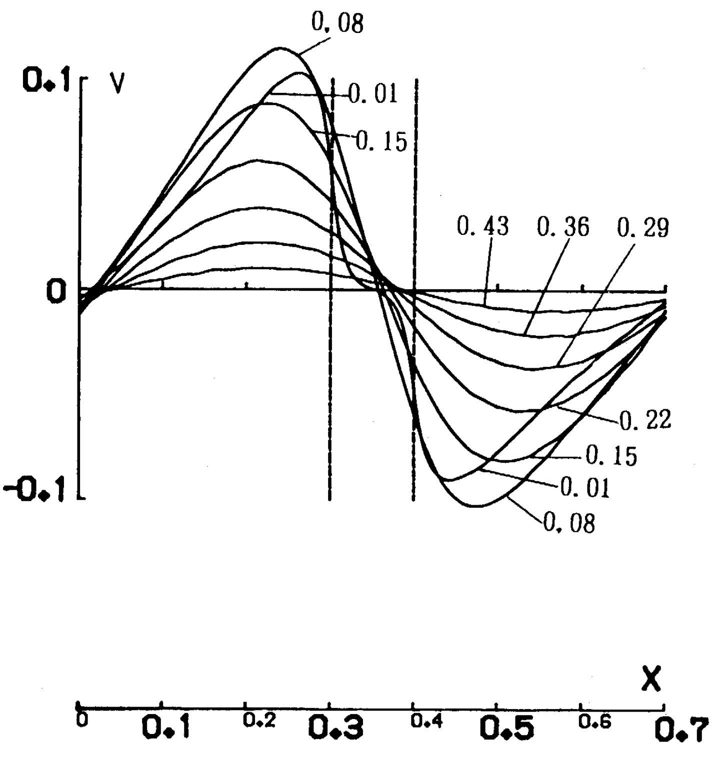

Fig. 4 Distribution of the normal velocity component v at the constant height (W/h=7 and Re=5), Flow is left to right.

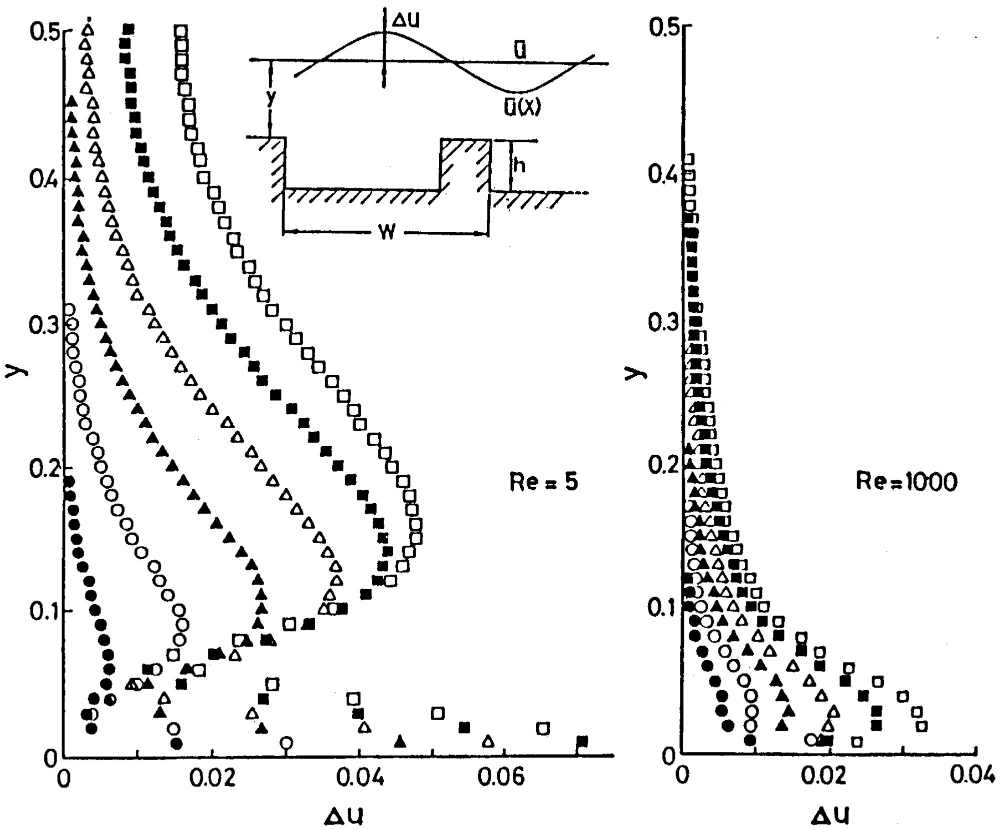

Fig. 5 $\triangle u$ profiles (Re=5, 1000 and W/h=2~7).

roughness groove). In addition, the profile of $\triangle u(y)$ is shown together with $v(y)$ in order to research the relation between $\triangle u(y)$ and $v(y)$. As shown in Fig.6, the minimum point of $v(y)$ is located on the portion over the rib. Here, for the case of $W/h=2$ and $Re=1000$ (Fig. 6(c)), the maximum point of $v(y)$ is located at the position of $y<0$, so the minimum point of $\triangle u(y)$ does not appear apparently.

3.3. *Relation between the vortex pattern in the roughness groove and the flow pattern over the rough wall*

With the object of an examination on how far the roughness effects extend, the distance Y from top of rib, where the value Y is determined at the location of $\triangle u(y)/\tilde{u}(y)=0.01$, is plotted in Fig.7 for the range of $5\leqq \mathrm{Re}\leqq 1000$ as the parameter of $W/h=2\sim 7$. From Fig. 7, it is found that the distance Y is proportional to the $\log Re$, thus, it may be represented by the expression

$$Y=A\log Re+B, \tag{3}$$

where A and B denote the constant depending on the pitch ratio W/h.

Next, the relation between vortex pattern in the roughness groove and this distance Y is investigated. For all cases of W/h and Re, the flow pattern in the roughness groove corresponding to the value of $Y<0.2$ is the one vortex type, and that of $Y>$

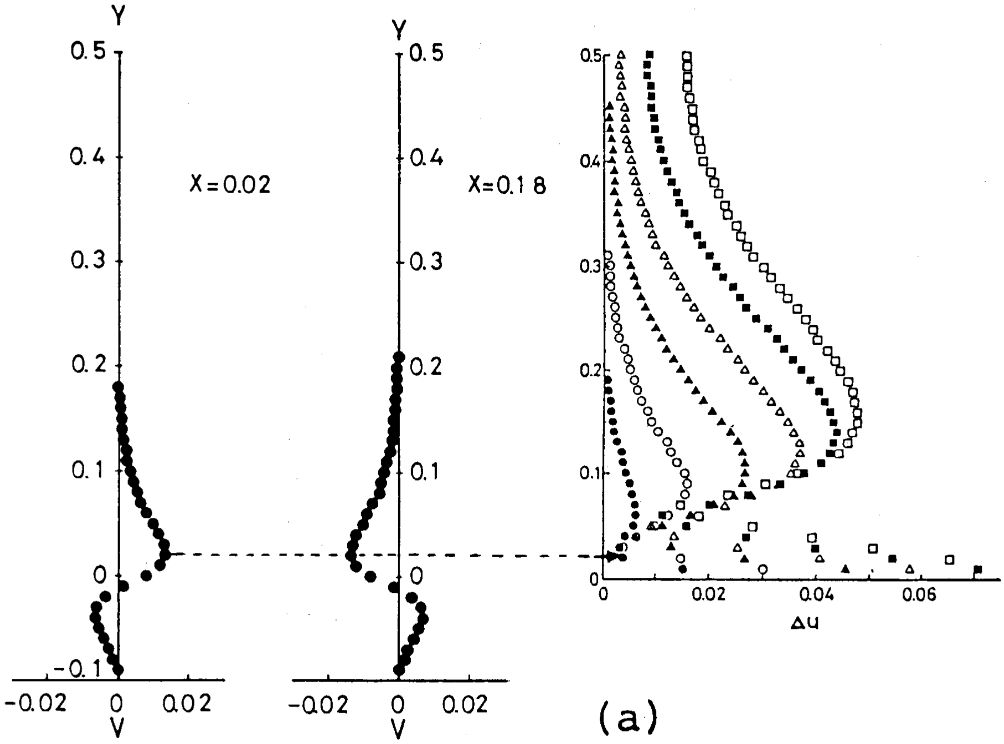

Fig. 6 (a) Profiles of the normal velocity component v (W/h=2 and Re=5)

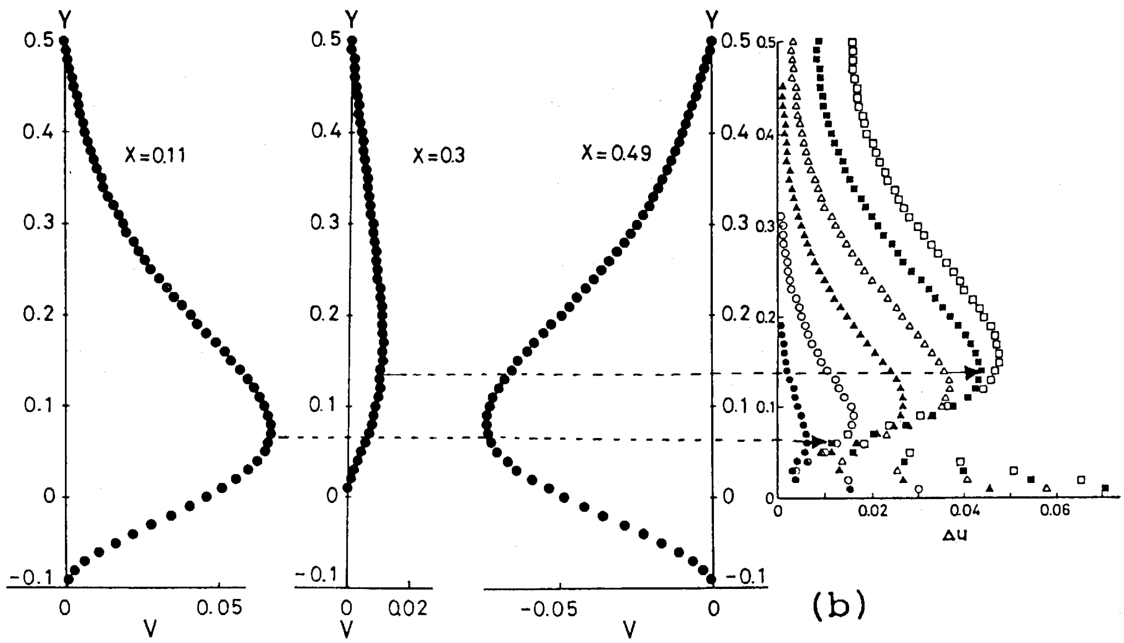

Fig. 6 (b) Profiles of the normal velocity component v (W/h=6 and Re=5)

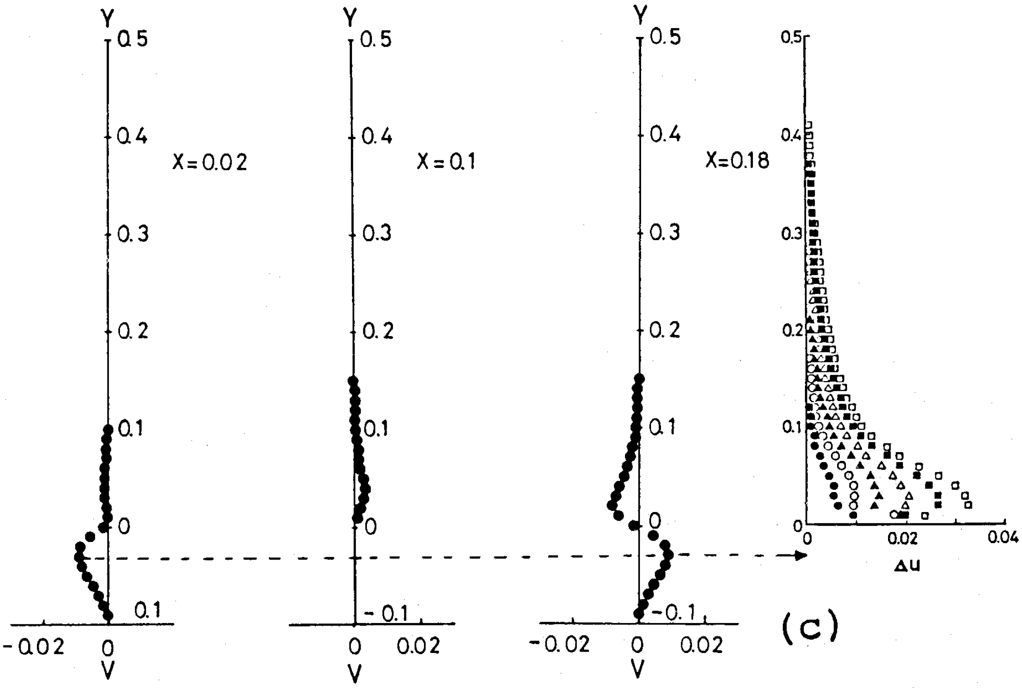

Fig. 6 (c) Profiles of the normal velocity component v (W/h=2 and Re=1000)

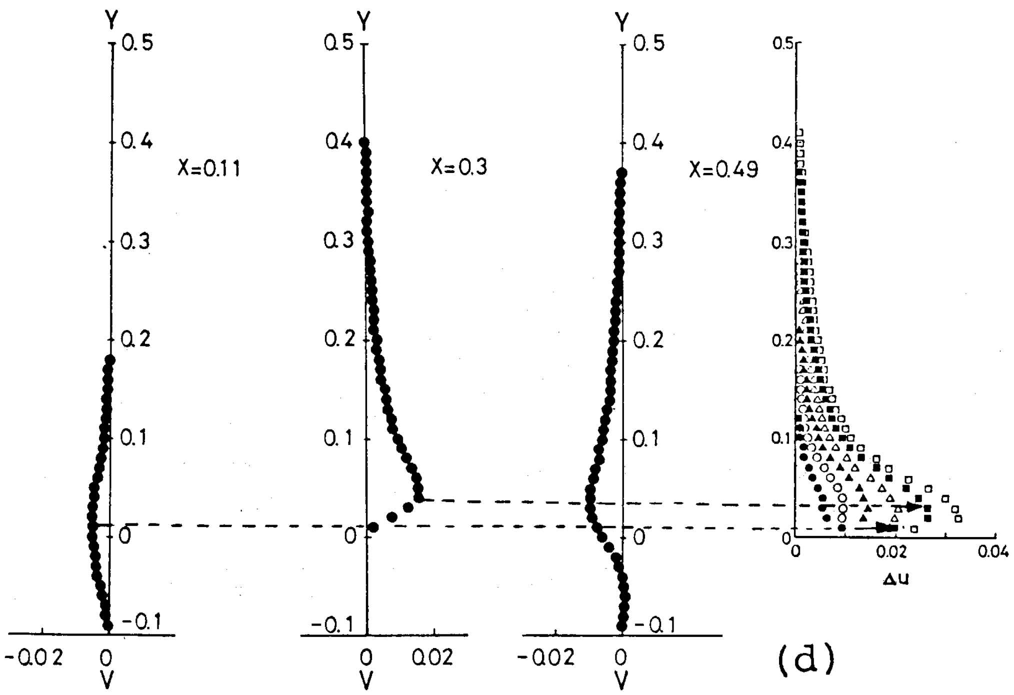

Fig. 6 (d) Profiles of the normal velocity component v (W/h=6 and Re=1000)

0.247 is the two vortex type. In the limited region of $0.2 < Y < 0.247$, the vortex pattern shows the semi-two vortex type. Here, as for example, the calculated vortex patterns corresponding to the region of marked with labels A, B and C in Fig.7. are shown in Fig.8 (for the detailed vortex pattern, refer to the previous paper [9] by authors). So the vortex pattern in the roughness groove can be predicted and classified by the value of Y, that is, by the flow pattern over the roughness elements.

4. Conclusion

From the results and the discussion described above, the following conclusions are summarized;

1) The periodic velocity distribution is observed in the similitude of roughness geometry, and the velocity near the wall increases above the roughness groove, otherwise decreases at the portion over the rib. On the other hand, that of central region shows contrary results.

2) The region in the tendency of increasing velocity above the groove and decreasing velocity over the rib is $0 < y < 0.05$, and that of contrary result is $0.05 < y$.

3) The form of periodic velocity distribution $\tilde{u}$, in the limited region of $0.04 < y < 0.07$ shows higher-mode compared with that of central region, however, the form of higher-mode resulting from non-linear effects does not appear in the distribution of v.

4) The amplitude of periodic flow $\triangle u$ decreases as the pitch ratio decreases, and decreases as the Reynolds number increase.

5) $\triangle u(y)$ shows the profile with maximum and minimum points.

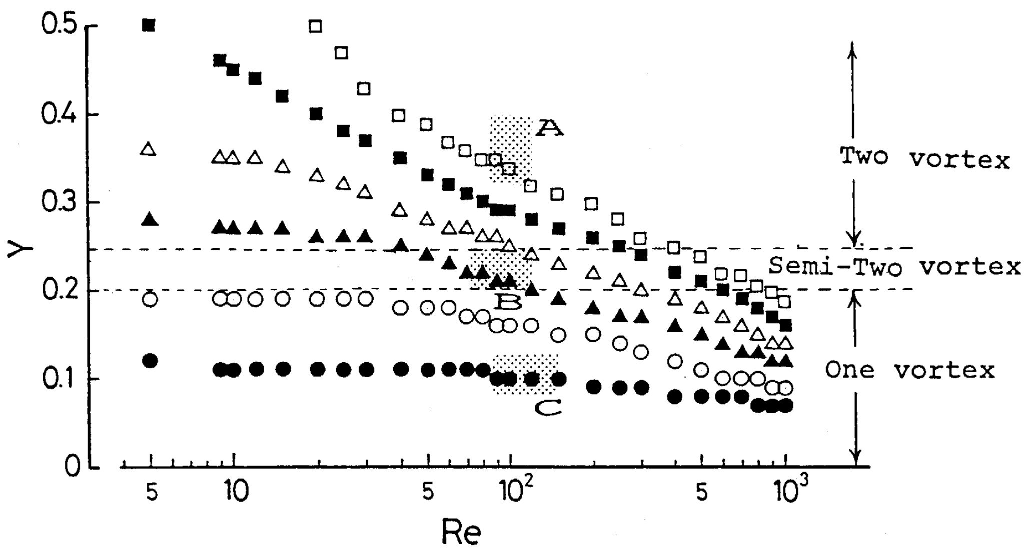

Fig. 7 Relation between the distance Y and the Reynolds number. Y is determined at the location of $\triangle u(y)/\tilde{u}(y)=0.01$

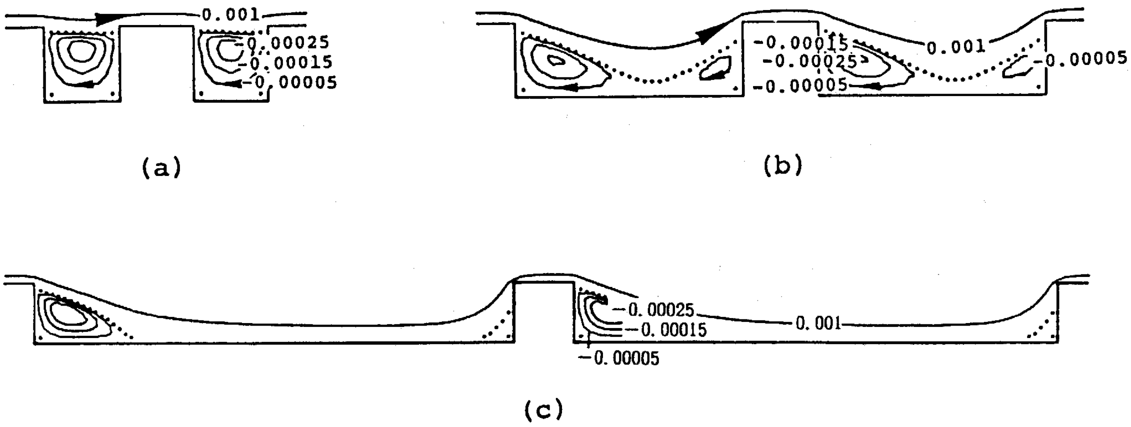

Fig. 8 Vortex pattern in the roughness groove (Stream lines)
(a) One vortex type (region of marked with label C in Fig.7),
(b) Semi-two vortex type (region of marked with label B in Fig 7),
(c) Two vortex type (region of marked with label A in Fig 7).

6) The minimum points of $\triangle u(y)$ correspond to the maximum point of $v(y)$, and maximum point of $\triangle u(y)$ is almost corrresponded to the maximum point of $v(y)$ on the portion over the rib.

7) The distance Y, which is determined at the location of $\triangle u(y)/\tilde{u}(y)=0.01$, may be represented by the expression $Y=A\log Re+B$, where A and B are the constant depending on the pitch ratio W/h.

8) The flow pattern in the roughness groove corresponding to the value of $Y<0.02$ is the one vortex type, and that of $Y>0.247$ and $0.2<Y<0.247$ are the two vortex type and semi-two vortex type, respectively. So the vortex pattern in the roughness groove can be predicted by the value of Y.

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